Electrical and Optical Characterization of Semiconductors

R. K. Ahrenkiel

Measurements and Characterization Division
National Center for Photovoltaics
National Renewable Energy Laboratory
Golden, Colorado 80401

03532043

Electro-Optical Characterization Team
R. K. Ahrenkiel: Team Leader and Research Fellow

- Recombinaton Lifetime Characterization

- Photoluminescence Spectroscopy

- Deep Level Transient Spectroscopy (DLTS)

- Fourier Transform Infrared Spectroscopy

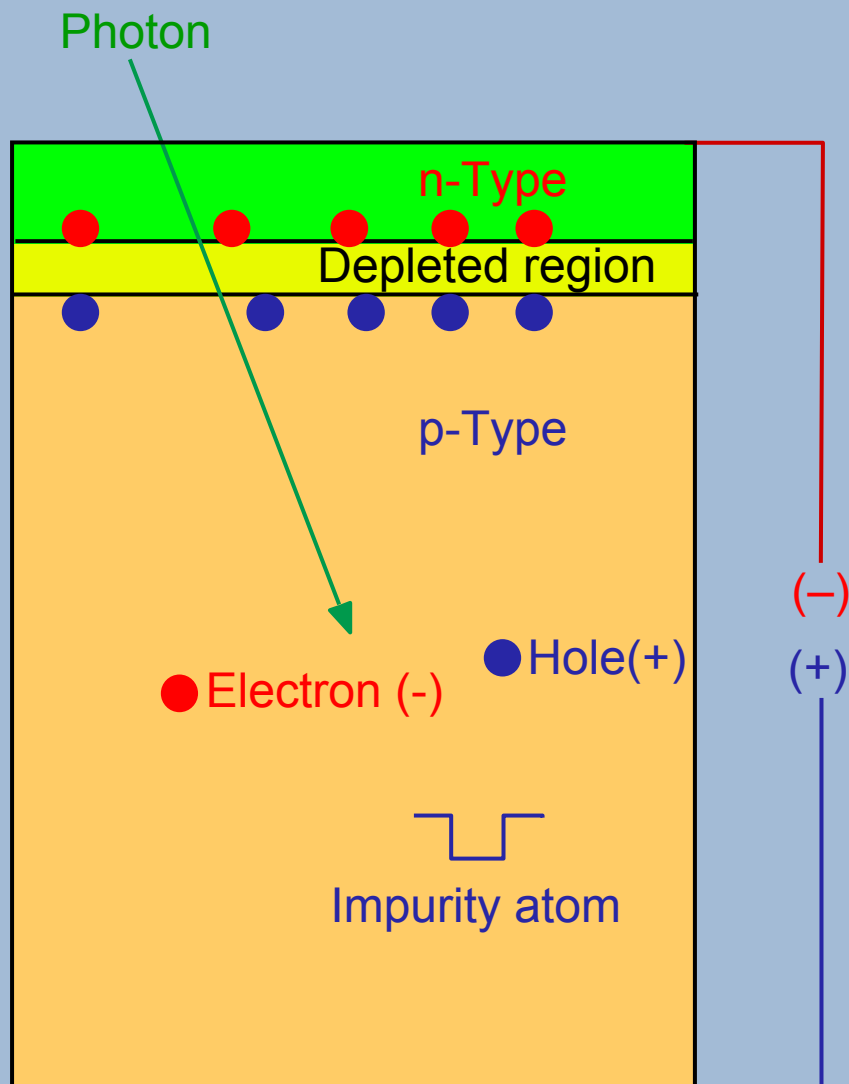- Scanning Ellipsometry

- Technique Development

03532044

Electro-Optical Characterization Team
R. K. Ahrenkiel: Team Leader and Research Fellow

- R. K. Ahrenkiel: Photoconductive Lifetime (RCPCD)

- Pat Dippo: Energy Resolved Photoluminescence

- Brian Keyes: Fourier Transform Spectroscopy

- Dean Levi: Ellipsometry

- Bhushan Sopori: Technique Development

- Wyatt Metzger: Photoluminescence Lifetime and Device Modeling

- Steve Johnston: Deep Level Transient Spectroscopy

- Lynn Gedvilas: Fourier Transform Spectroscopy

- Four Graduate Students: J. Dashdorj and J. Luther (CSM), Sung Ho Han (CU-Boulder), Chuan Li (New Jersey Institute of Technology)
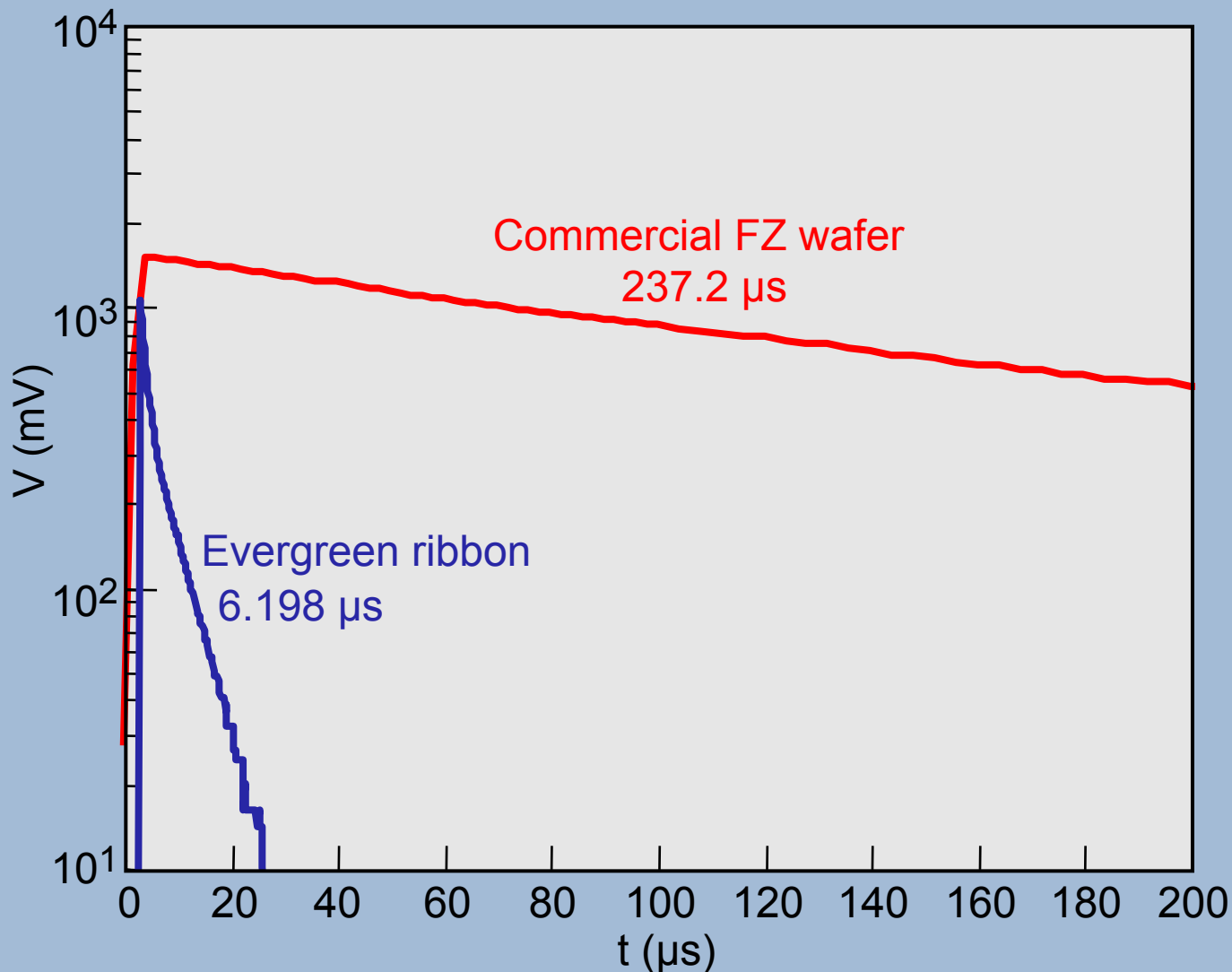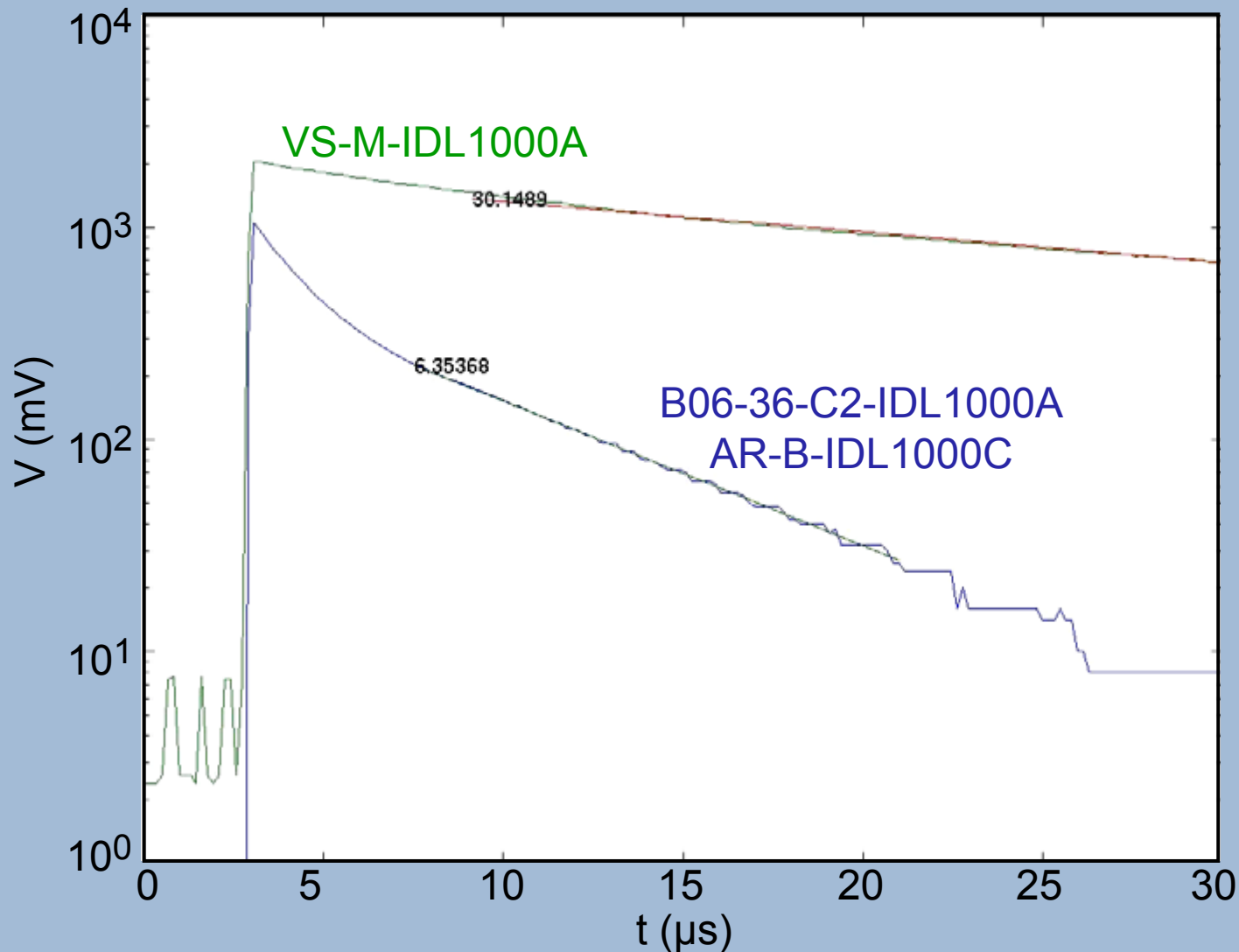
- Sabbatical: (9/04) Prof. Tim Gfroerer

03532045

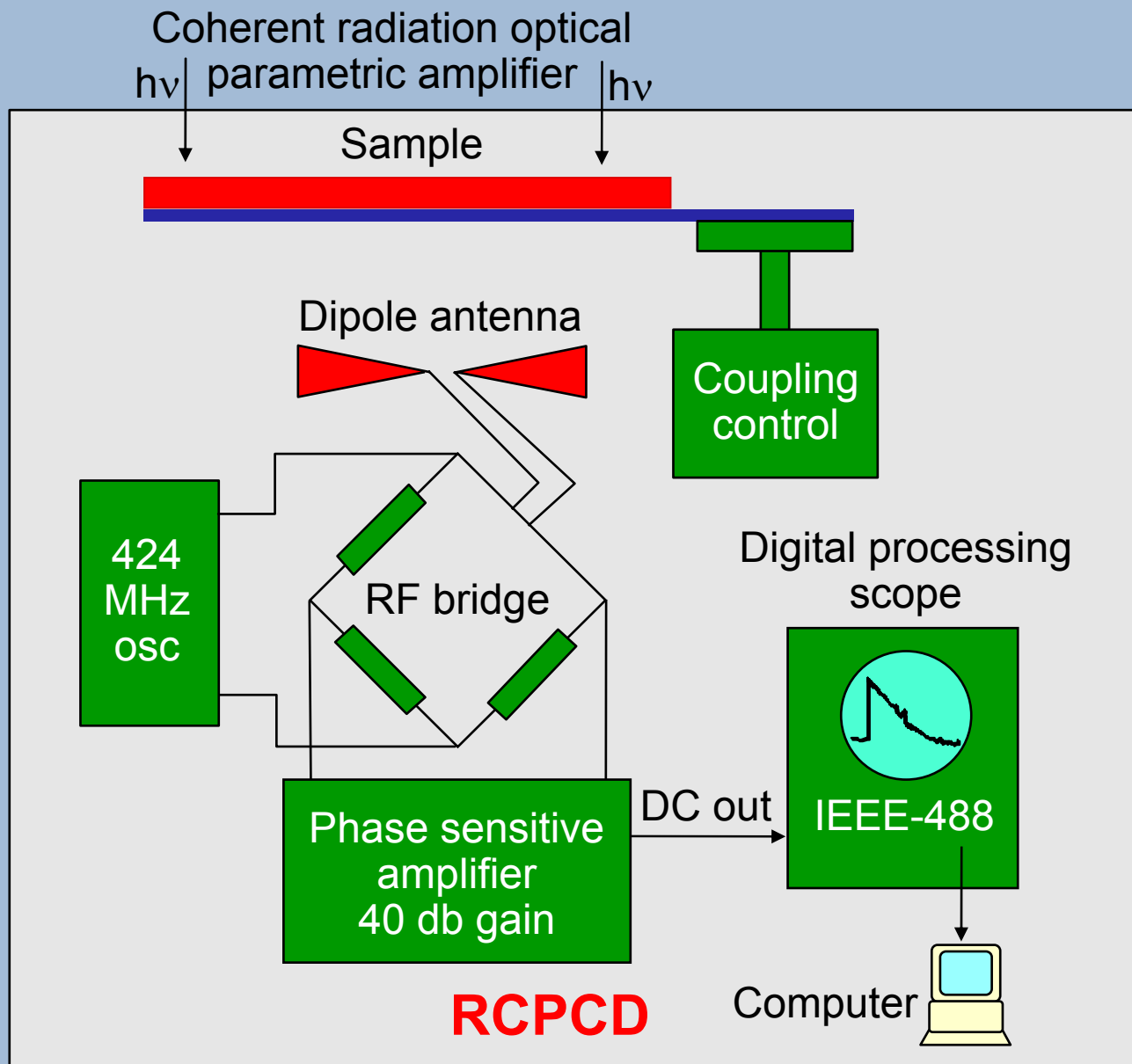# Resonance-coupled Photoconductive Decay

03532047

RCPCD Composite

VS-M-IDL1000A

B06-36-C2-IDL1000A
AR-B-IDL1000C

30.1489

6.35368

V (mV)

t (µs)

03532048

Coherent radiation optical
parametric amplifier

hν $\qquad$ hν

Sample

Dipole antenna

Coupling
control

424
MHz
osc

RF bridge

Digital processing
scope

IEEE-488

Phase sensitive
amplifier
40 db gain

DC out

RCPCD

Computer

03532049

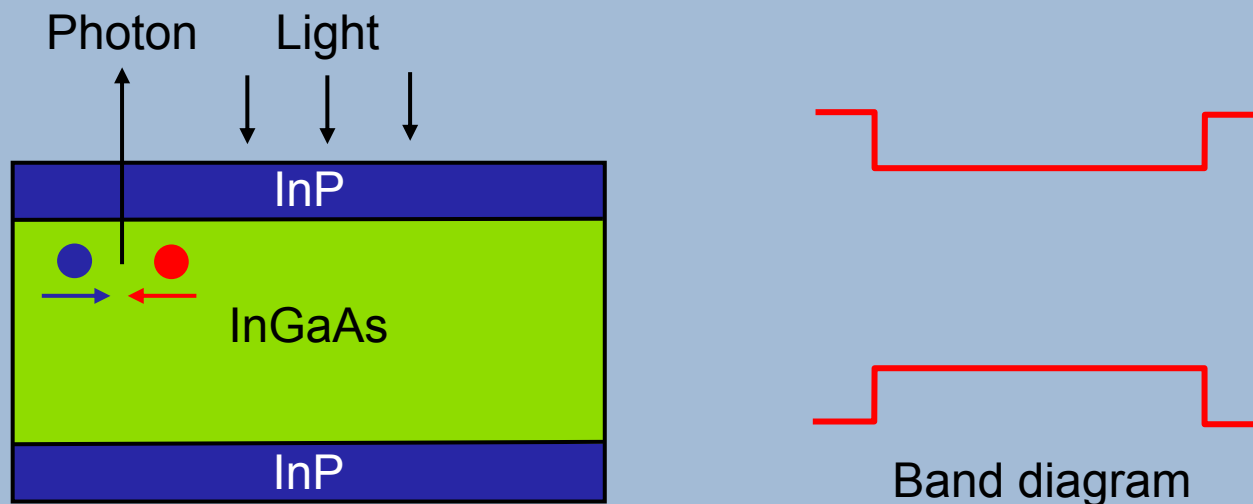# Time-resolved Photoluminescence and Lifetime Measurements

Time-resolved Photoluminescence

- Inject excess carriers into a sample with laser causing photoluminescence

- Watch the photoluminescence intensity decay

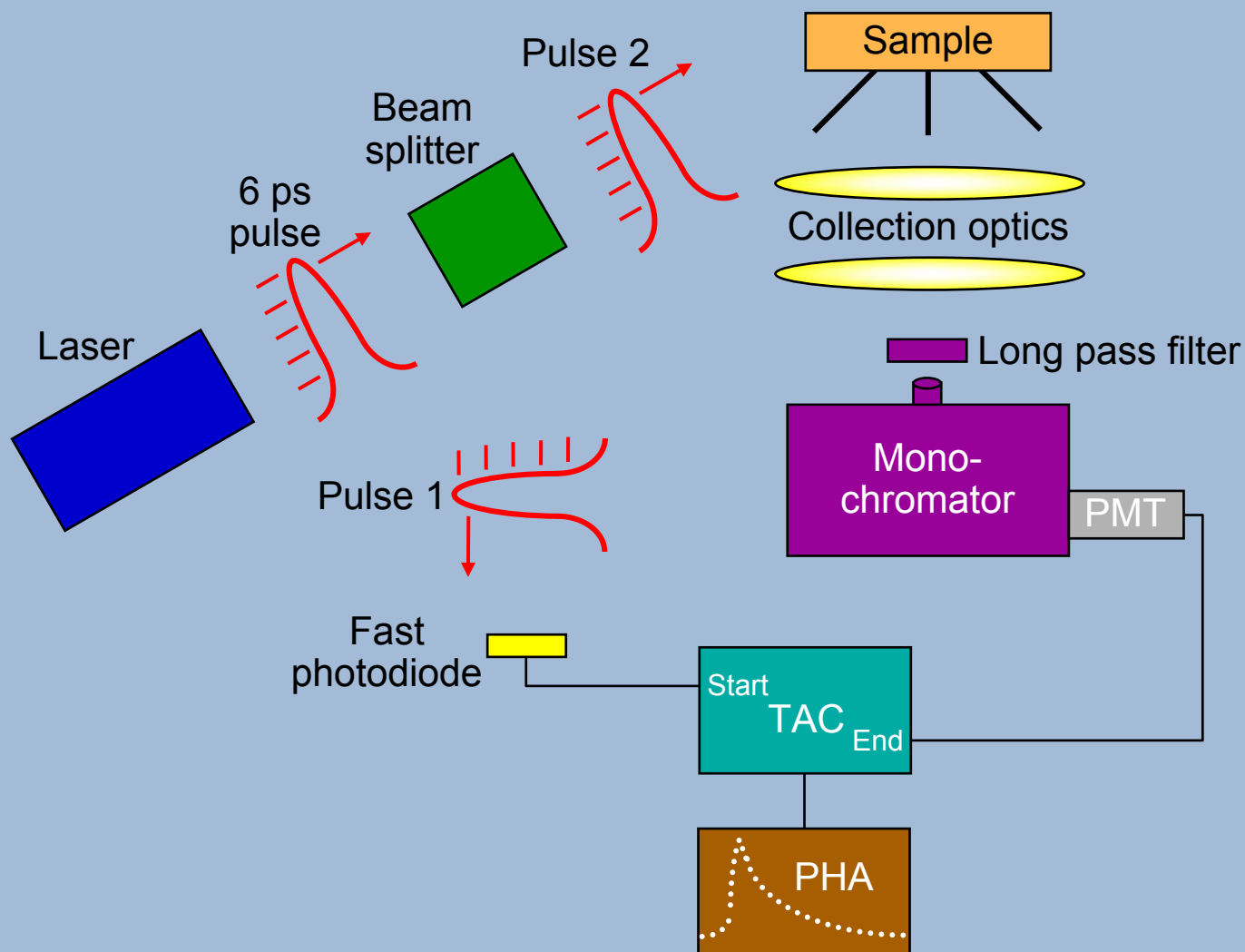- Use a semiconductor diode, single photon counting, up-conversion TRPL

03532051

The Sample

Photon   Light

InP

InGaAs

InP

Band diagram

- Double heterostructure confines carriers and provides surface passivation

- Cap layers are generally very thin and transparent to PL and incident laser light

- Not limited to this structure, but preferable

03532052

Single Photon Counting Schematic

Pulse 2

Sample

Beam splitter

Collection optics

6 ps pulse

Laser

Long pass filter

Mono-chromator

Pulse 1

PMT

Fast photodiode

Start

TAC End

PHA

1. We count a photon once in about 300 attempts.

2. We make 1 million attempts per second.
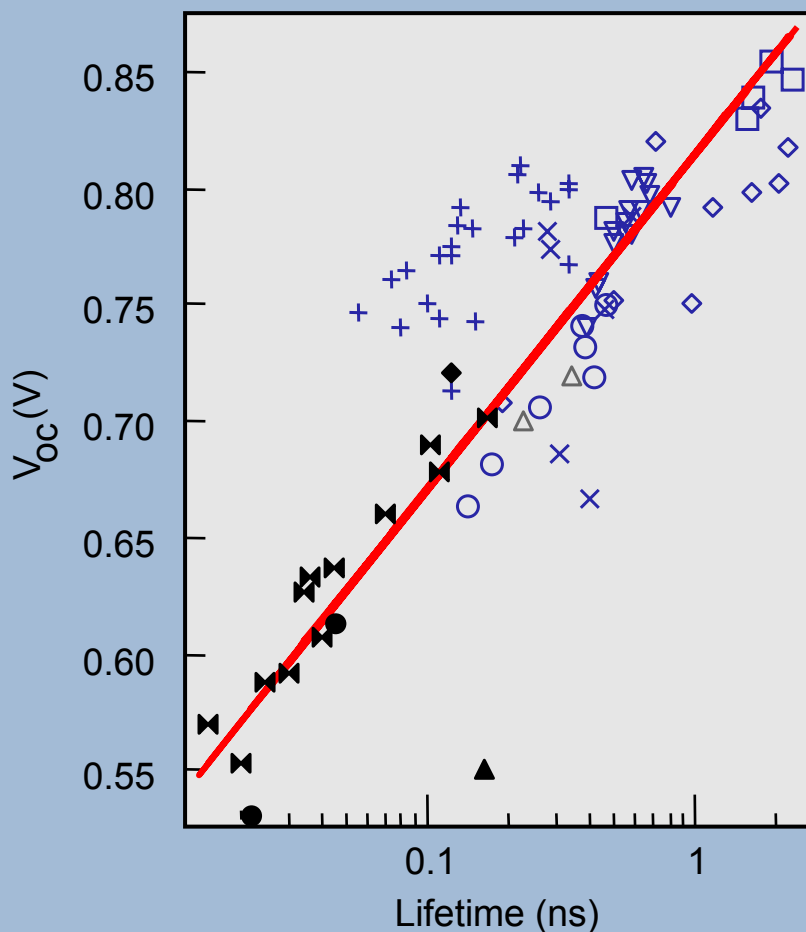
3. We finish with a histogram of photon counts vs. time.

03532053

Results

03532054
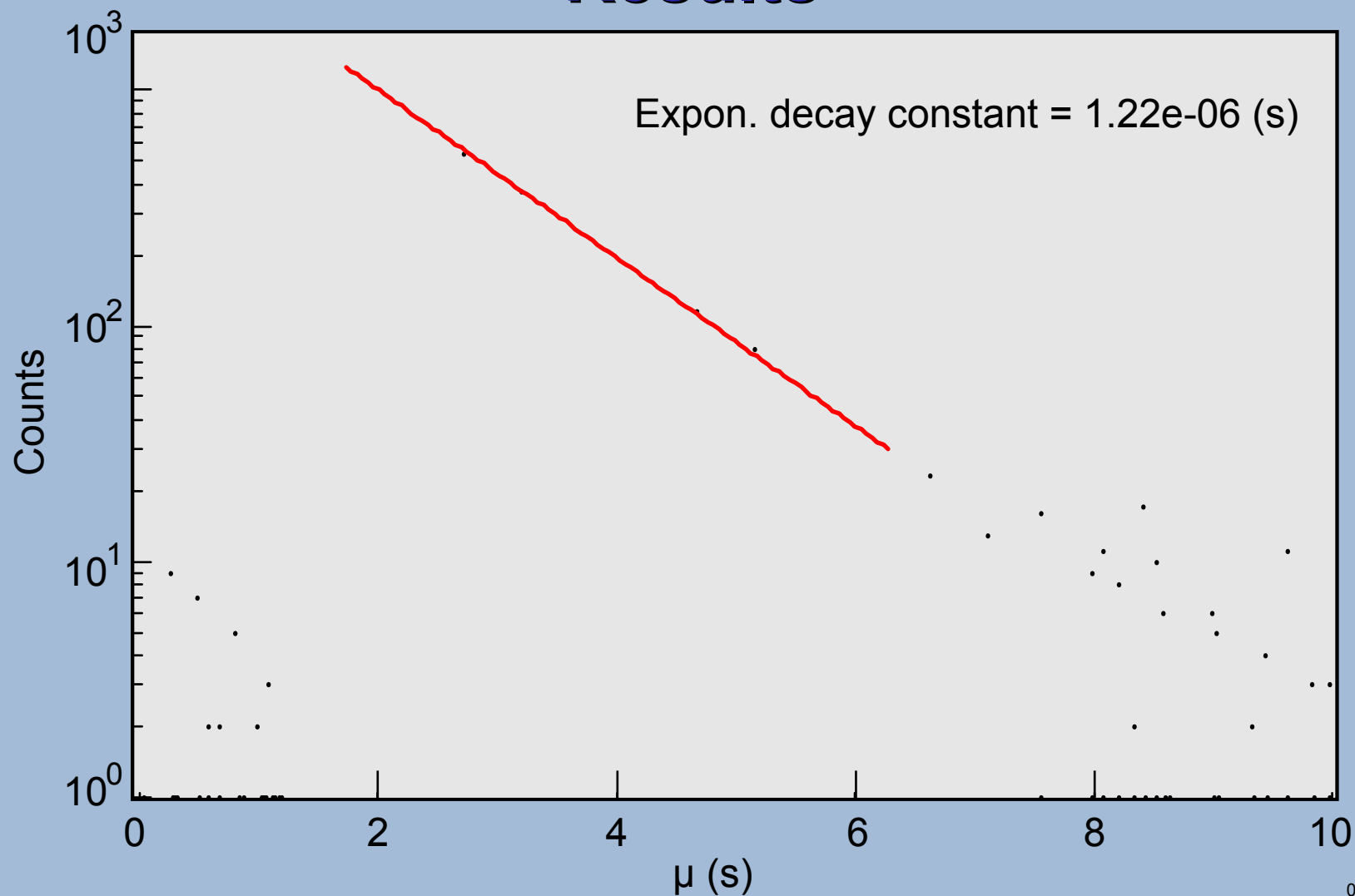
Lifetime often Correlated with V_{oc}

CdTe – *JAP* 94 (5): 3549-3555, Sep. 1, 2003

CIGS – Proceedings of the 29th IEEE pp.511–514, 2002

CIGS – *JAP* 94 (9): 5584–5591, Nov. 1, 2003

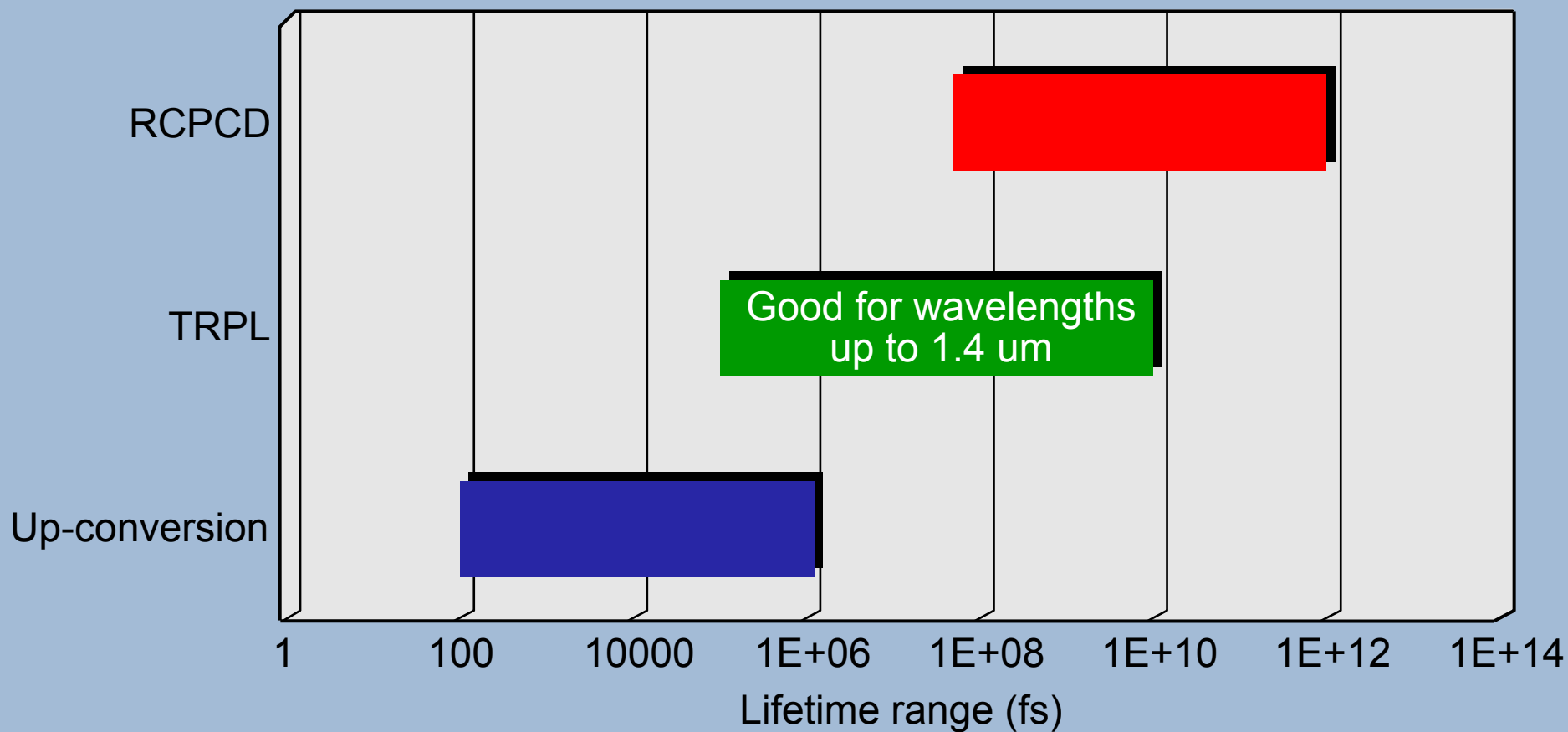CIGS – *APL* **73**(9): 1224-1226, 1998

CIGS – *Thin Solid Films* **387**: 262-267, 2001

GaInAs – 3rd World Conference on Photovoltaic Energy Conversion 2003

GaNP - *J. Cryst. Growth* 259 (3): 223–231, 2003

03532055

The Experimental Range

Lifetime range (fs)

RCPCD

TRPL — Good for wavelengths up to 1.4 um

Up-conversion

1   100   10000   1E+06   1E+08   1E+10   1E+12   1E+14

03532056

Lifetime Ranges for Different Materials

Material	Lifetime Range	Mechanism	Injection	Control
GaAs	Short - 22 μs	Radiative, SRH	yes	yes
GaInAs	100 fs - 10 μs	Auger, Radiative, SRH	yes	yes
GaInP	200 ps - 25 ns	Mostly SRH	no	some
CdTe	200 ps - 2ns	nonradiative	no	some
CIGS	300 ps - 3 ns	nonradiative	no	not monitored
GaNP	100 ps - 10 ns	nonradiative	no	Depends on N
GaInAsN	100 ps - 10 ns	nonradiative	no	Depends on N
GaAsN	100 ps - 10 ns	nonradiative	no	Depends on N
GaInN	100 ps - 10 ns	nonradiative	no	Depends on N

03532057

Deep Level Transient Spectroscopy
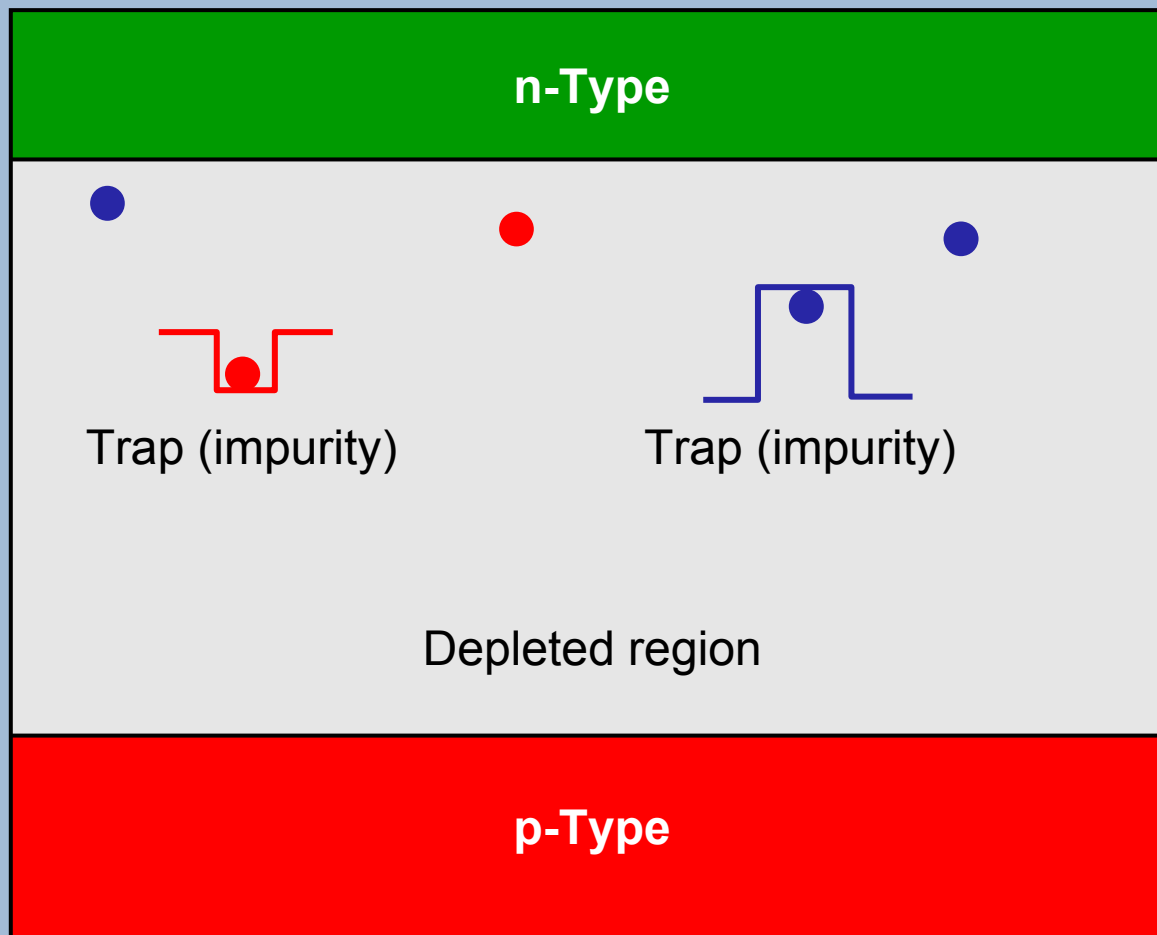
Laser for option of optical DLTS

Temperature controller
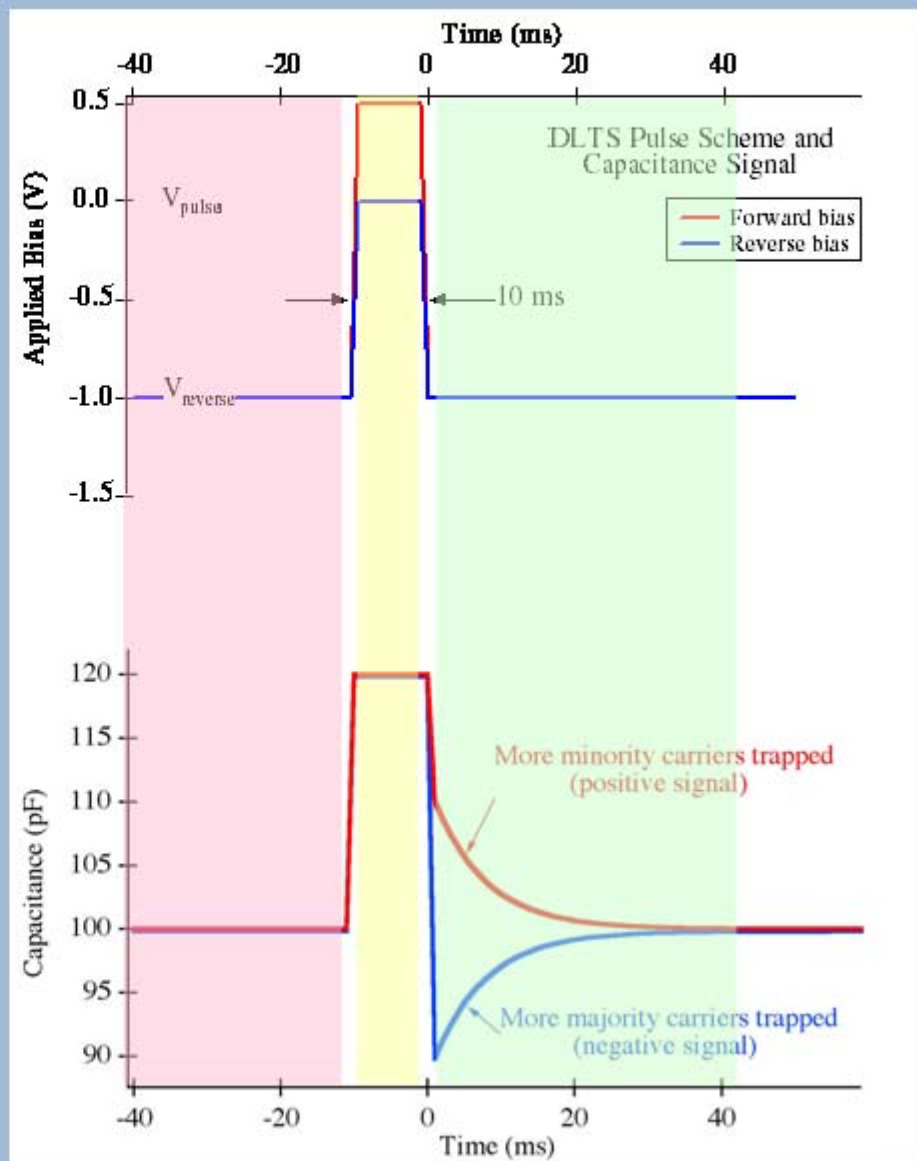
DLTS unit

Liquid nitrogen dewar
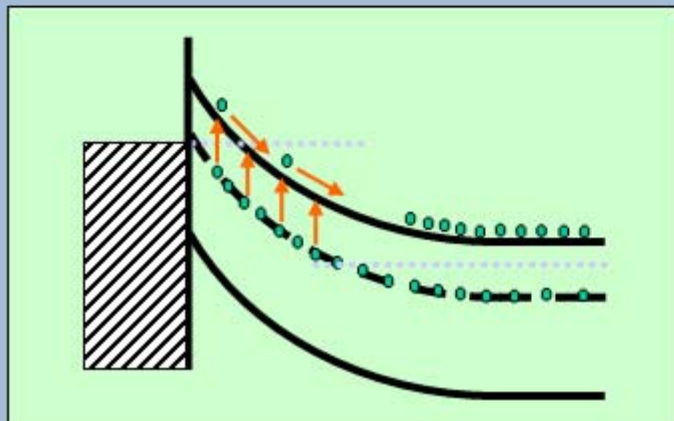
Oscilloscope to view signal

7/22/2003

03532058
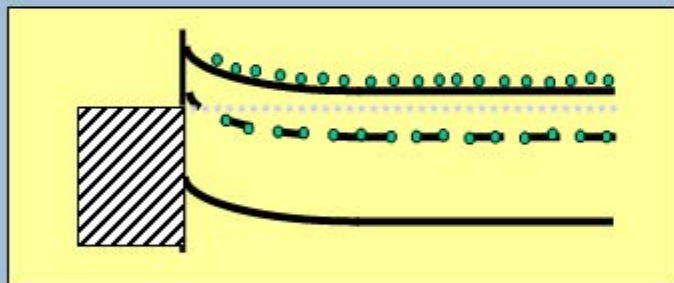
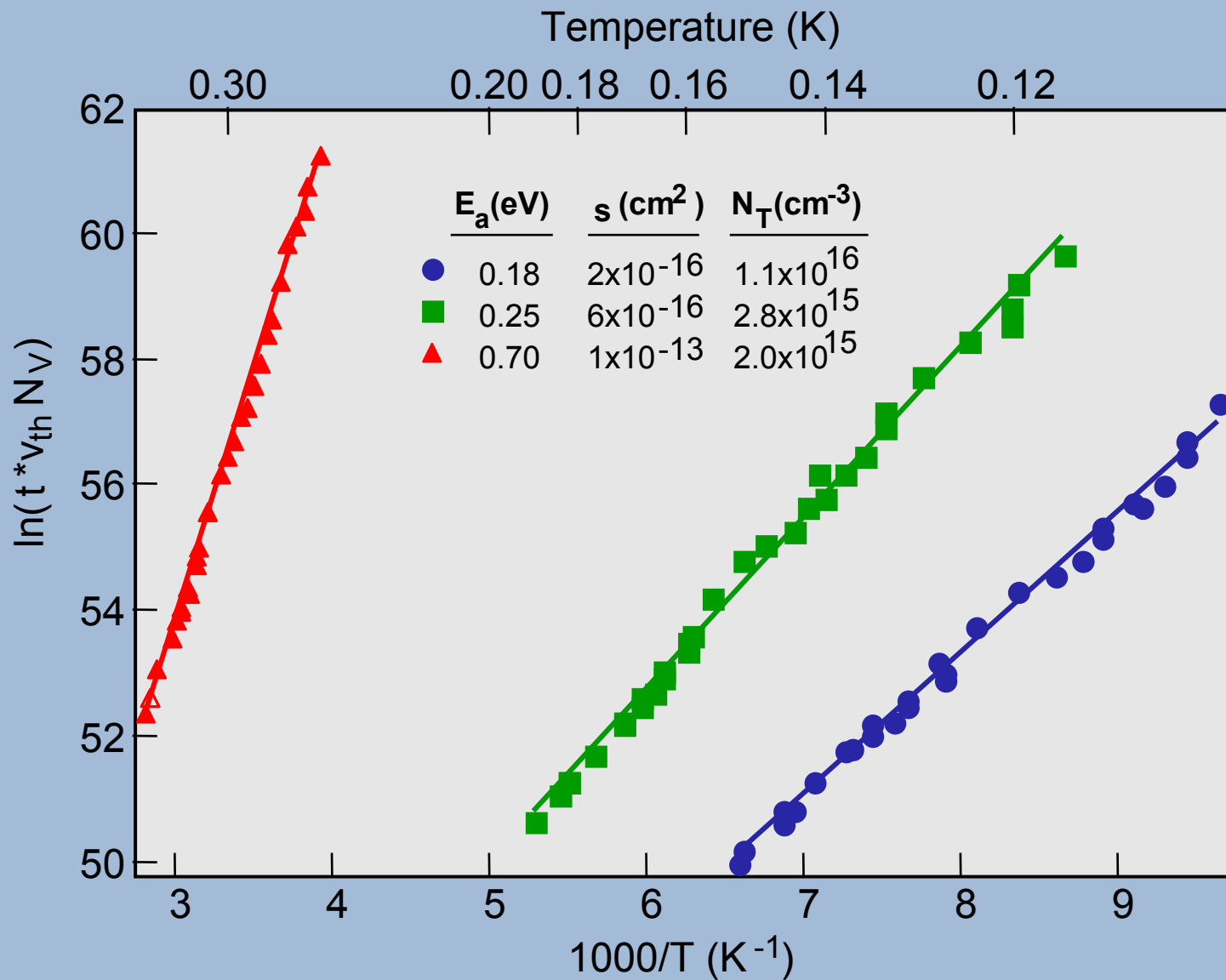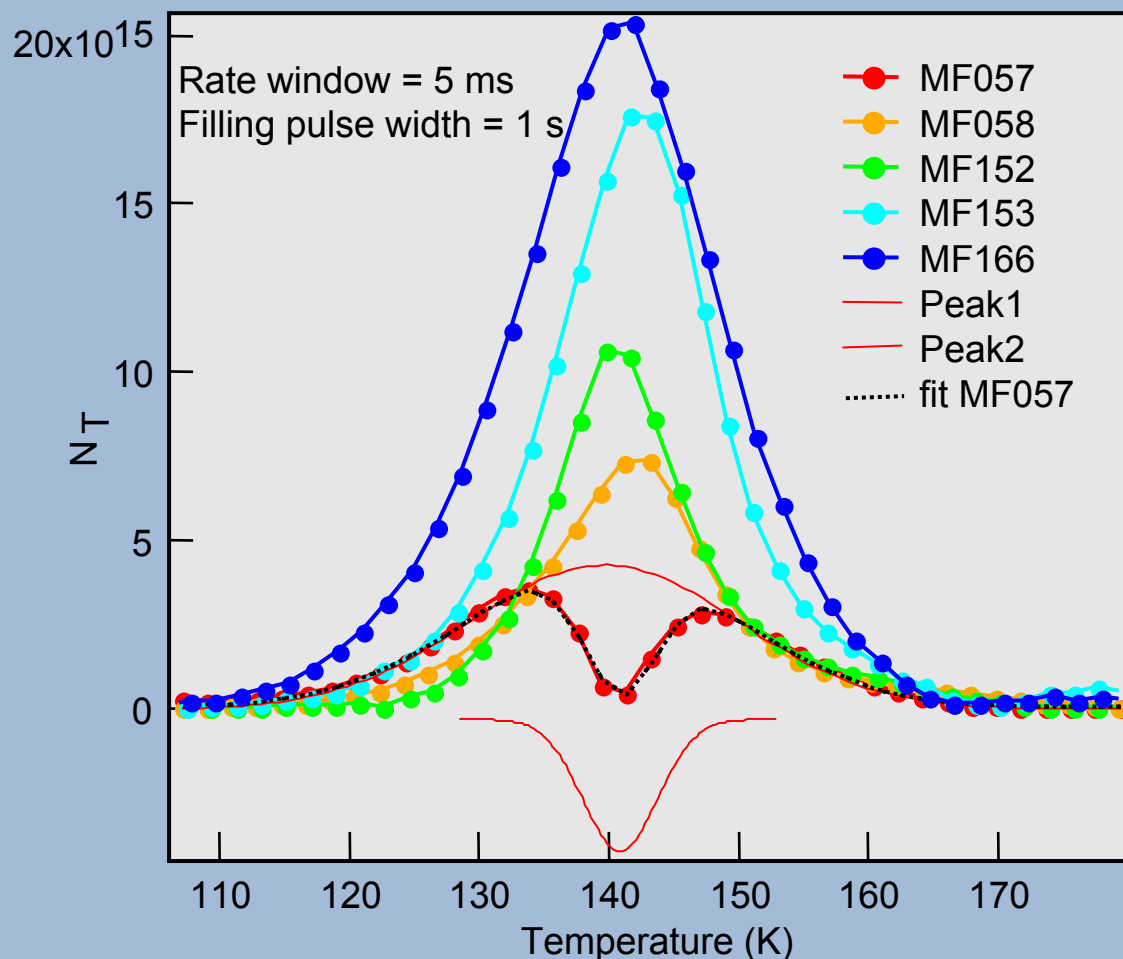# The Effects of Traps (Impurities)

Example: gold in silicon

03532059

03532060

DLTS Spectra

GaAs
25X

InGaAs
25X

InGaAsN
N=0.4%
3X

InGaAsN
N=2%
1X

GaAsN
1X

GaAsN
(ODLTS)
5X

Rate window = 0.43 ms
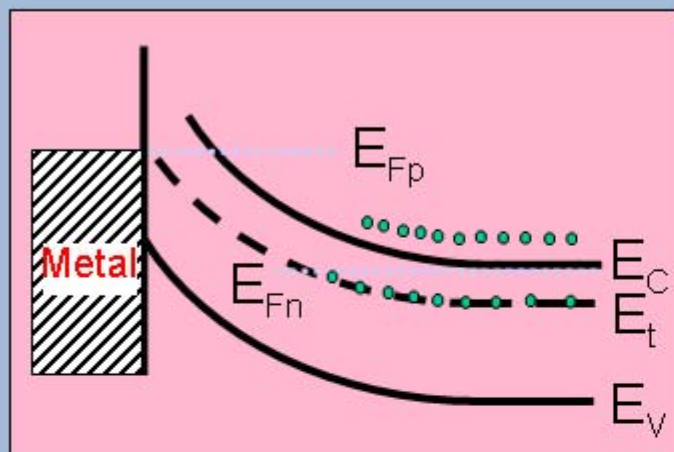
Arrhenius plot analysis on next slide

N_T (cm^{-3})
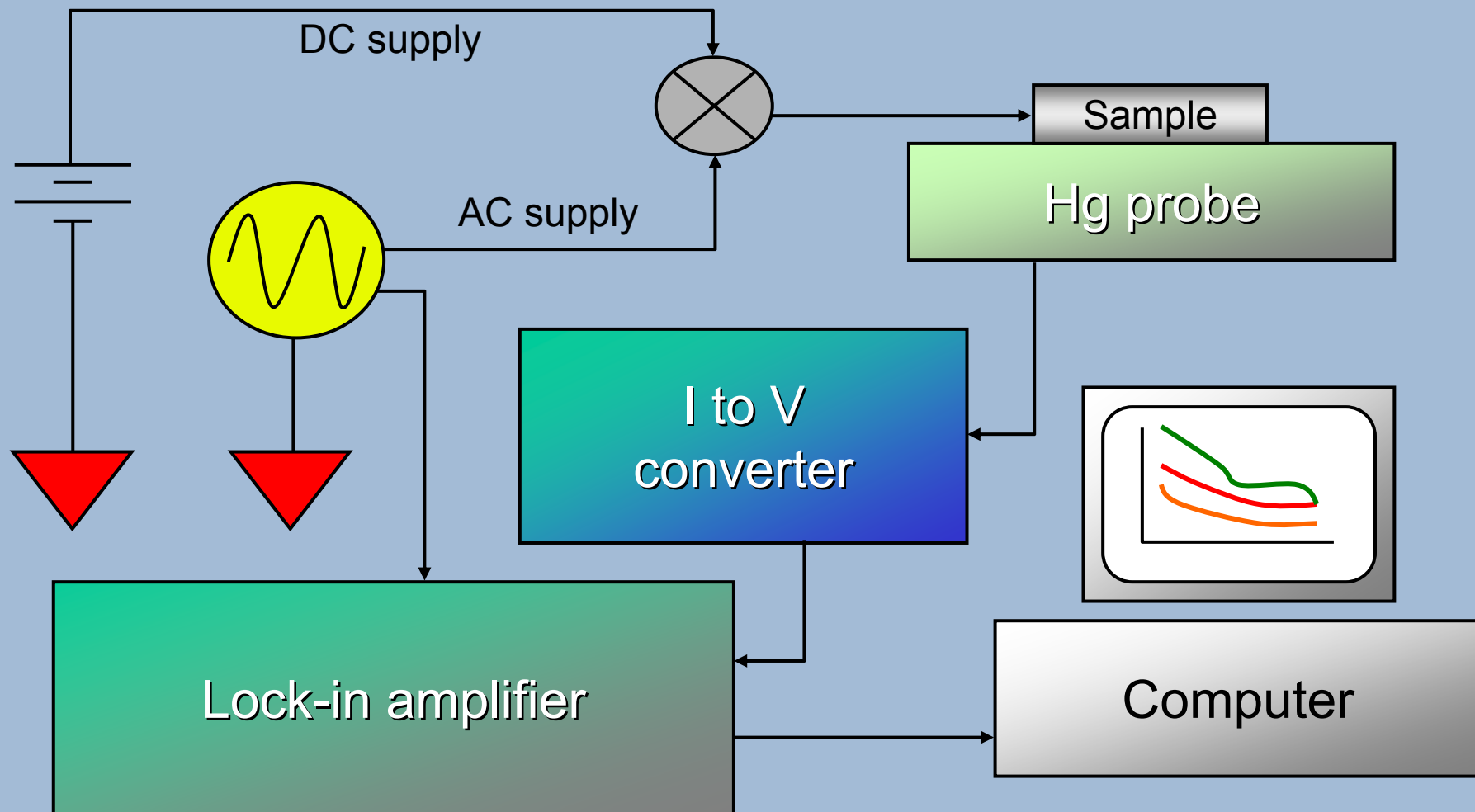
Temperature (K)

03532061

03532062
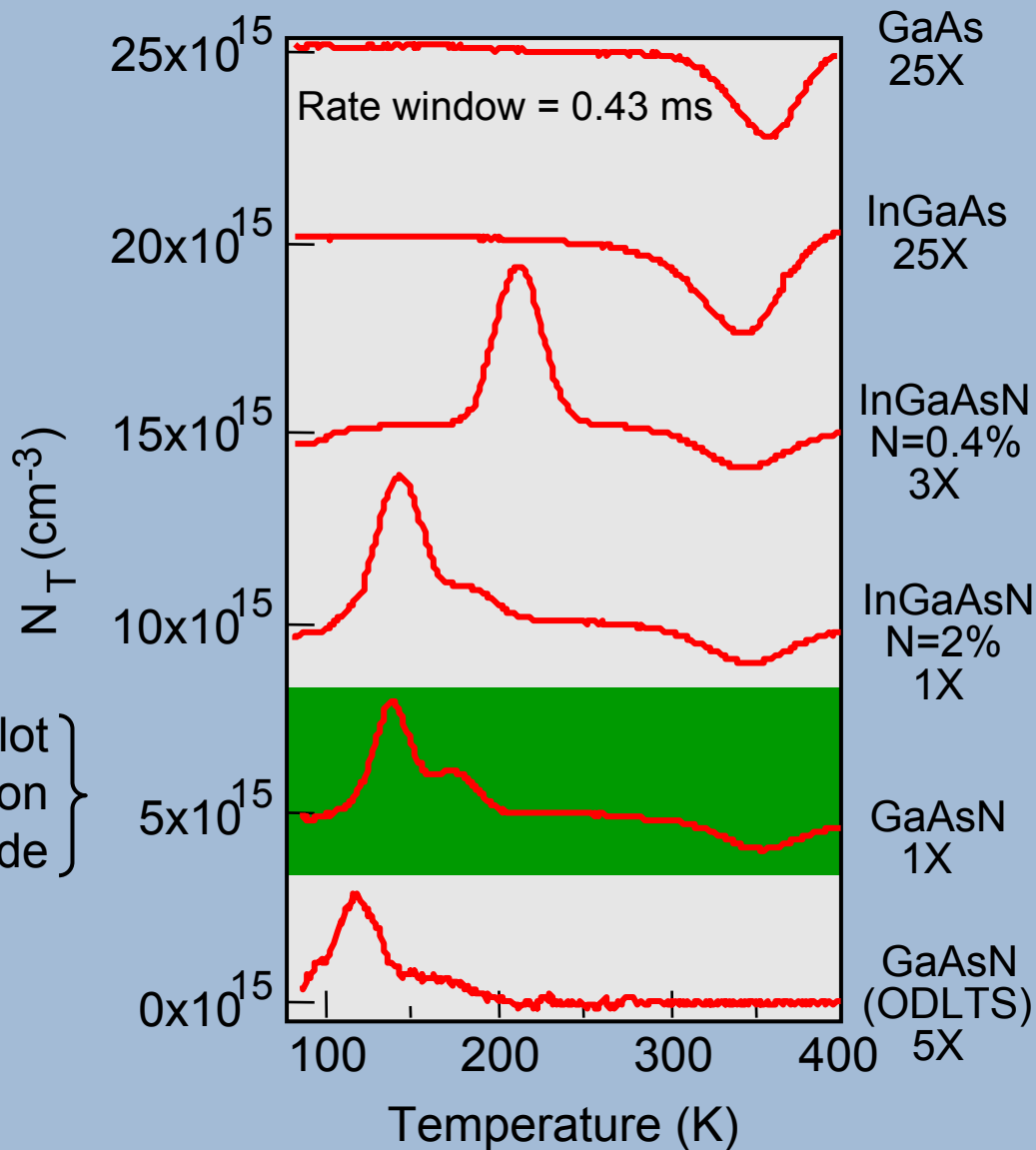
Concentration of Traps Corresponding with the Low-T Peak Increases with Increasing Amounts of N

The defect corresponding to this peak may be responsible for the low V_{oc} and poor solar cell performance of InGaAsN.

03532063

Drive Level Capacitance Profiling

DC supply

AC supply

Sample

Hg probe

I to V converter

Lock-in amplifier

Computer

03532064

Sample Data Using Drive Level Capacitance Profiling

Capacitance is plotted versus AC amplitude (plus an adjustment of DC) for several DC biases. Each curve is fit to a 2nd order polynomial to calculate the impurity density at a given depletion depth. This process is repeated for multiple AC frequencies.
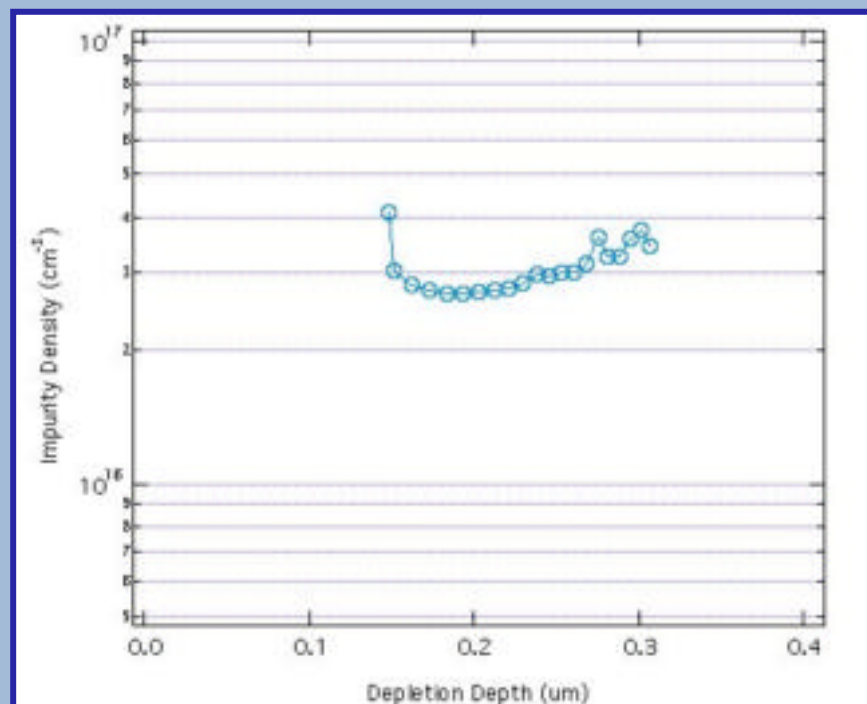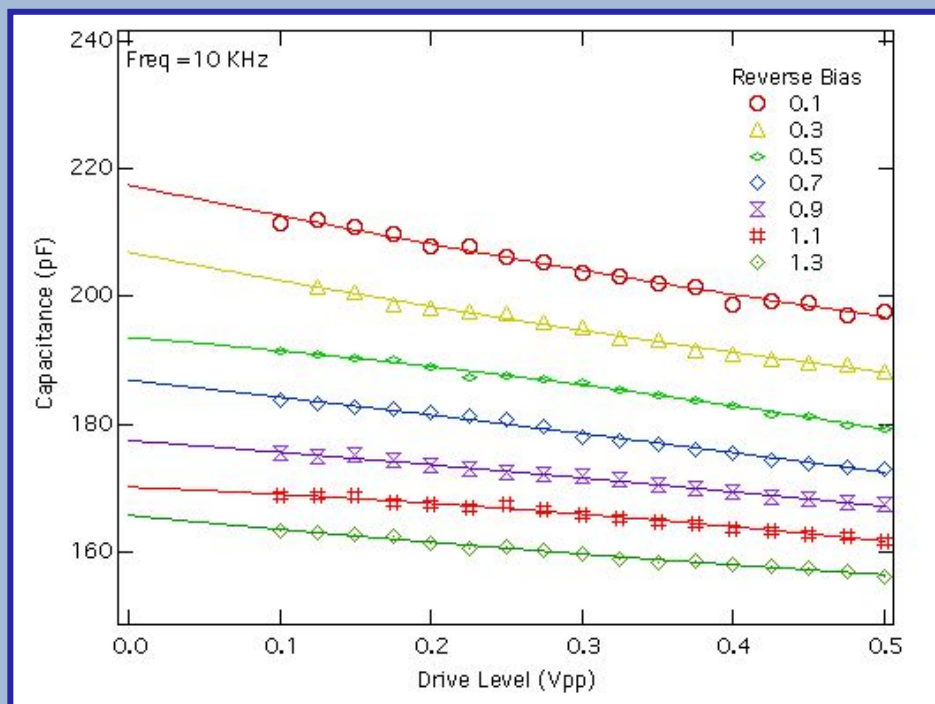
# Temperature Dependent Current-Voltage

03532066
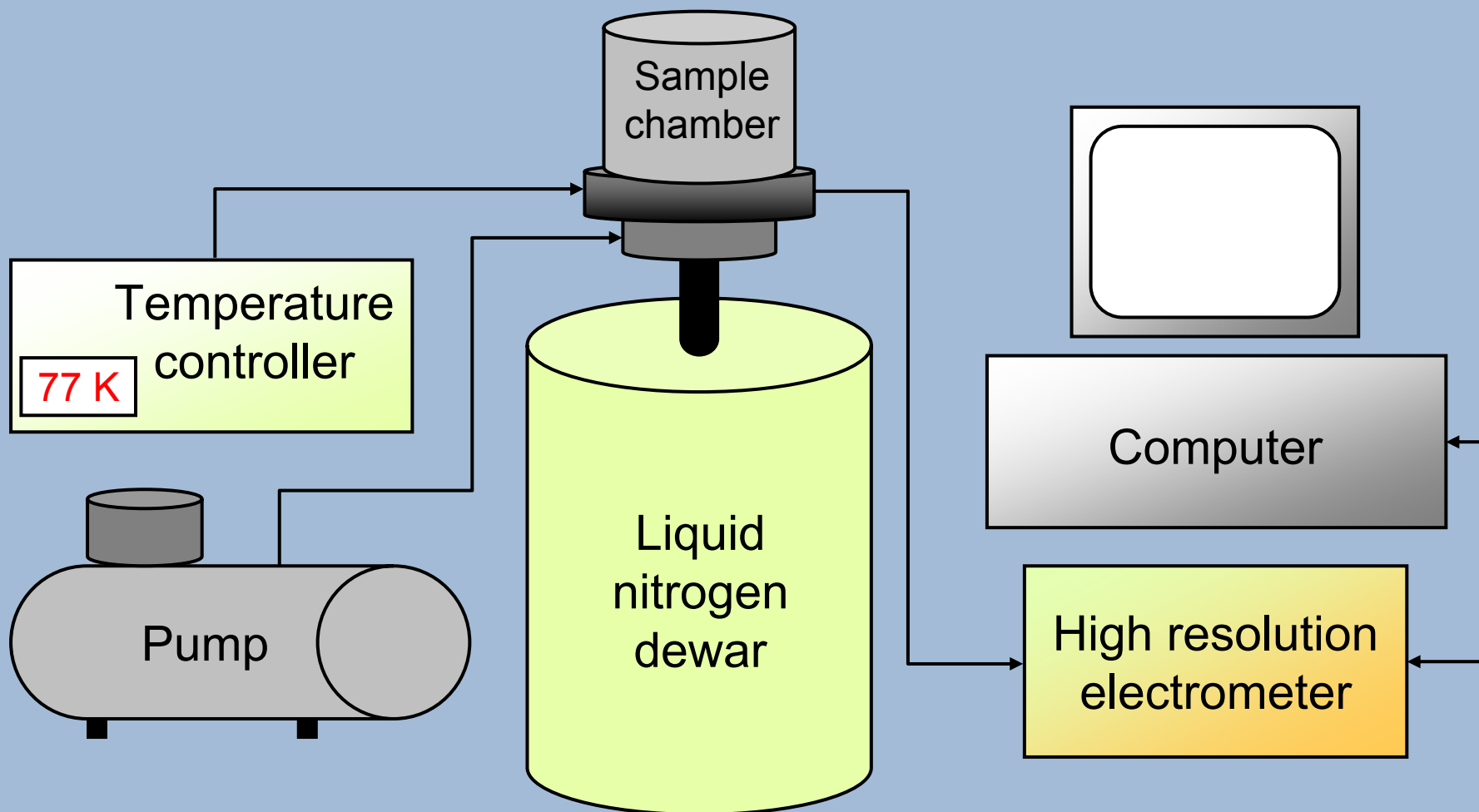
Sample Temperature Dependent IV Data

Current-Voltage measurements are taken as a sample is cooled down to liquid nitrogen temperature. The current density is then plotted in an Arrhenius plot for several reverse biases. The slope of this data can provide activation energies or insight into band diagram information.

03532067
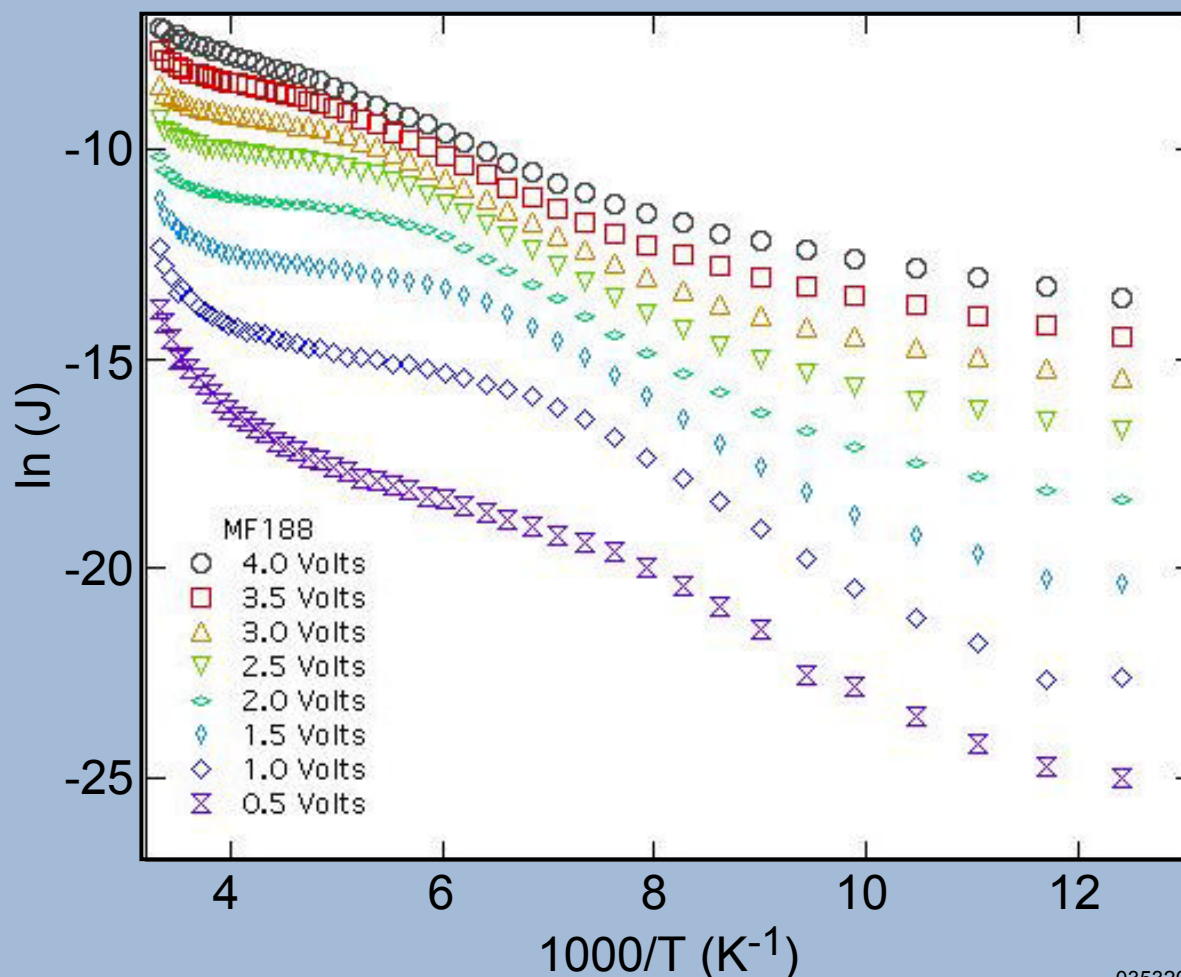
Energy Resolved Photoluminescence

- Energy resolved photoluminescence is a process that helps researchers determine the bandgap for a semiconductor material and also enables researchers to look for defects within those kinds of materials. The fewer defects a material has the more efficiently it will perform. Photoluminescence is the product of electron hole pairs recombining and producing photons. Those photons are emitted from within the bandgap and below the bandgap if there are defects.

- The experiment set up is very simple and straightforward. Collimated light (laser) is focused onto a semiconductor sample to excite the electrons above the bandgap. Many laser lines can be used. At NREL there are six CW laser lines available and they range between 325nm to 822nm. The photoluminescence is then collected through a lens collimated and focused onto a slit on an imaging spectrograph. This light is then passed through the spectrograph to either a CCD array or a photodiode array. The spectra is then acquired and recorded through data acquisition software onto a computer. It can then be analyzed and archived.

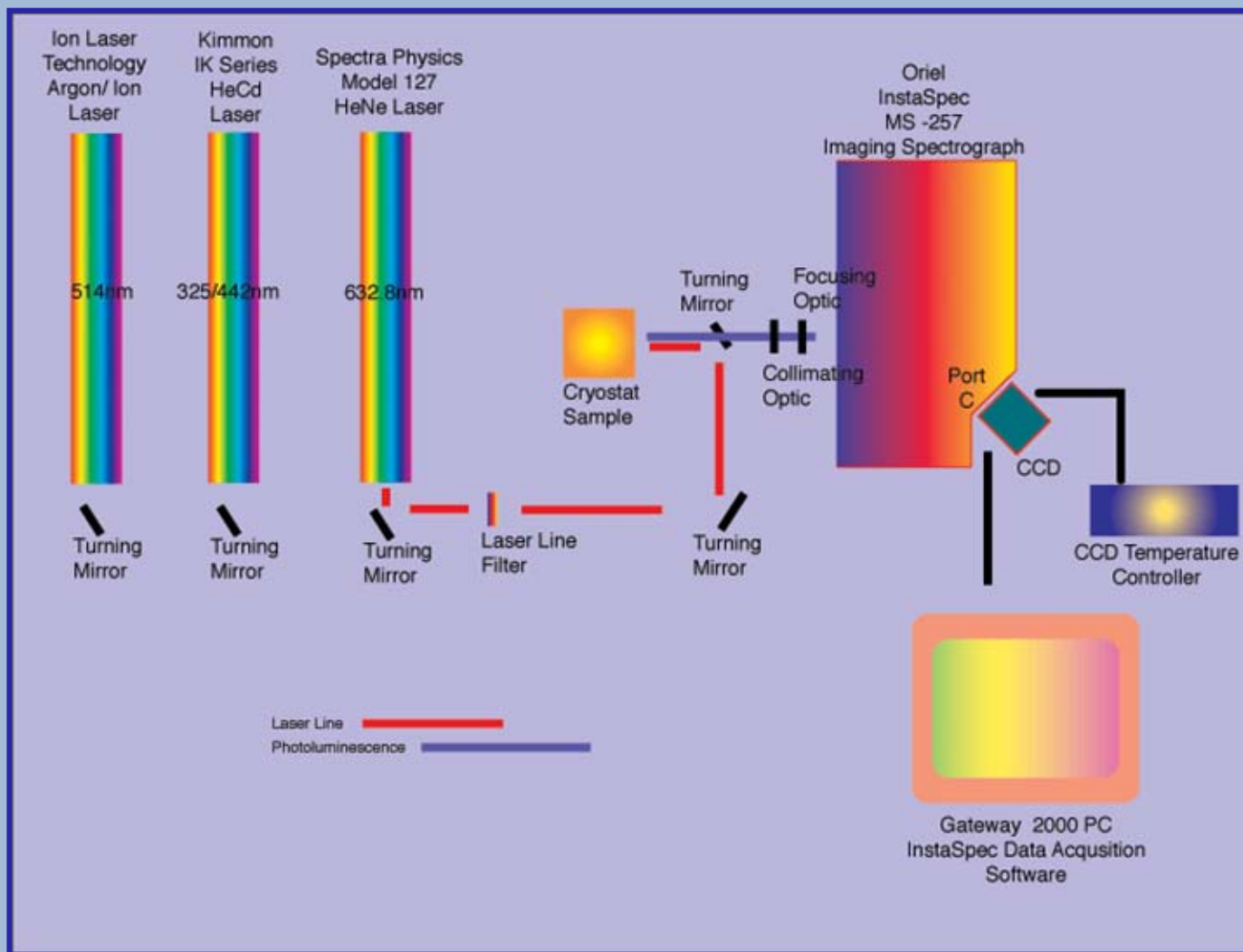# ERPL Measurement Using Continuous Flow (portable) Cryostat

03532069

ERPL Capabilities

- CCD (charge coupled device) Camera for PL measurements in the visible

- InGaAs PDA (photodiode array) for measurements in the NIR

- Imaging spectrometer with four gratings for use with the CCD and PDA

- InSb detector with a scanning monochromometer for measurements in the IR

- Ge detector with a triple grating monochromometer for high resolution measurements at longer wavelengths.

- Closed cycle cryostat which enables measurements to be performed at 4.25 K

- Temperature controller to allow temperature dependent measurements.

- Continuous flow cryostats that are portable and can be used with different setups in the laboratory (technique development)
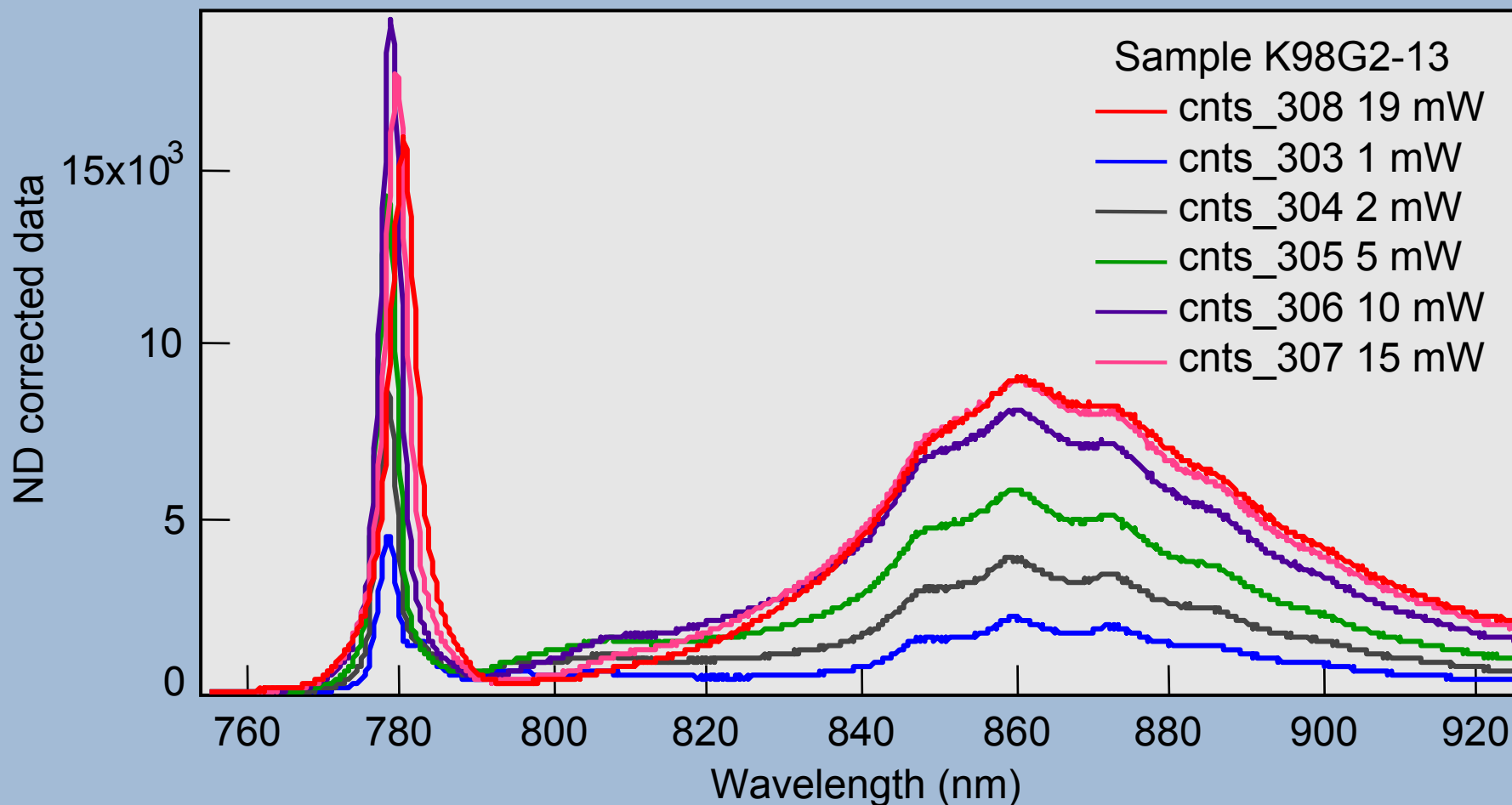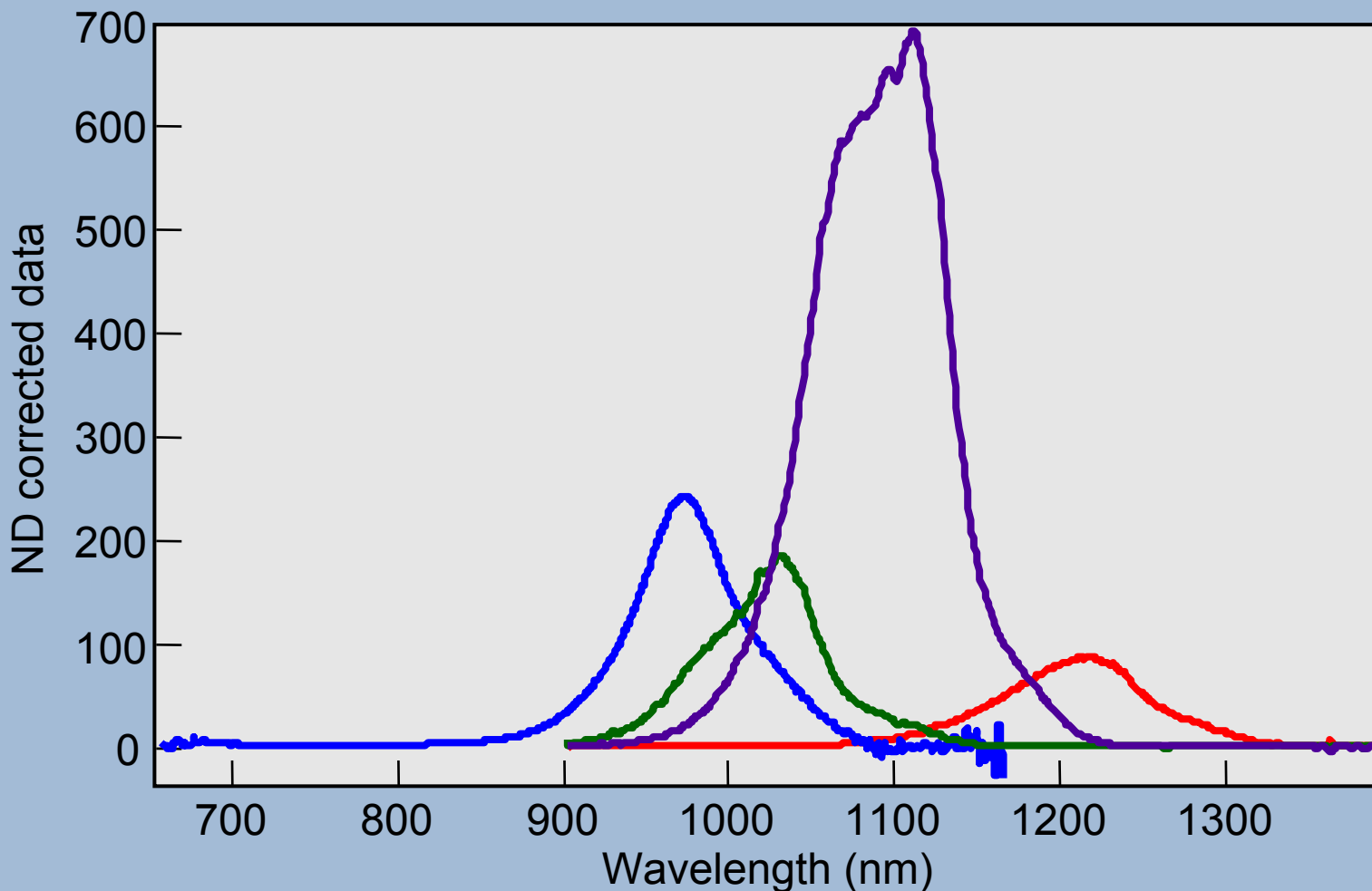
ERPL Setup Using the CCD Camera

03532071

PL Spectra of CdTe Film at 4.25K

Sample K98G2-13
- cnts_308 19 mW
- cnts_303 1 mW
- cnts_304 2 mW
- cnts_305 5 mW
- cnts_306 10 mW
- cnts_307 15 mW

Wavelength (nm)

ND corrected data

03532072

PL Spectra of CIS/CGS Material at Room Temperature

03532073

Fourier Transform Infrared (FTIR) Spectroscopy
## Brian M. Keyes and Lynn M. Gedvilas

- Reflectance, transmittance, and absorption measurements
- Spectral region is home to molecular and free carrier absorption
- Impurity analysis
- Bonding configurations
- Quantitative analysis
- Nondestructive
- Sensitivity advantages over dispersive systems
- Imaging capabilities
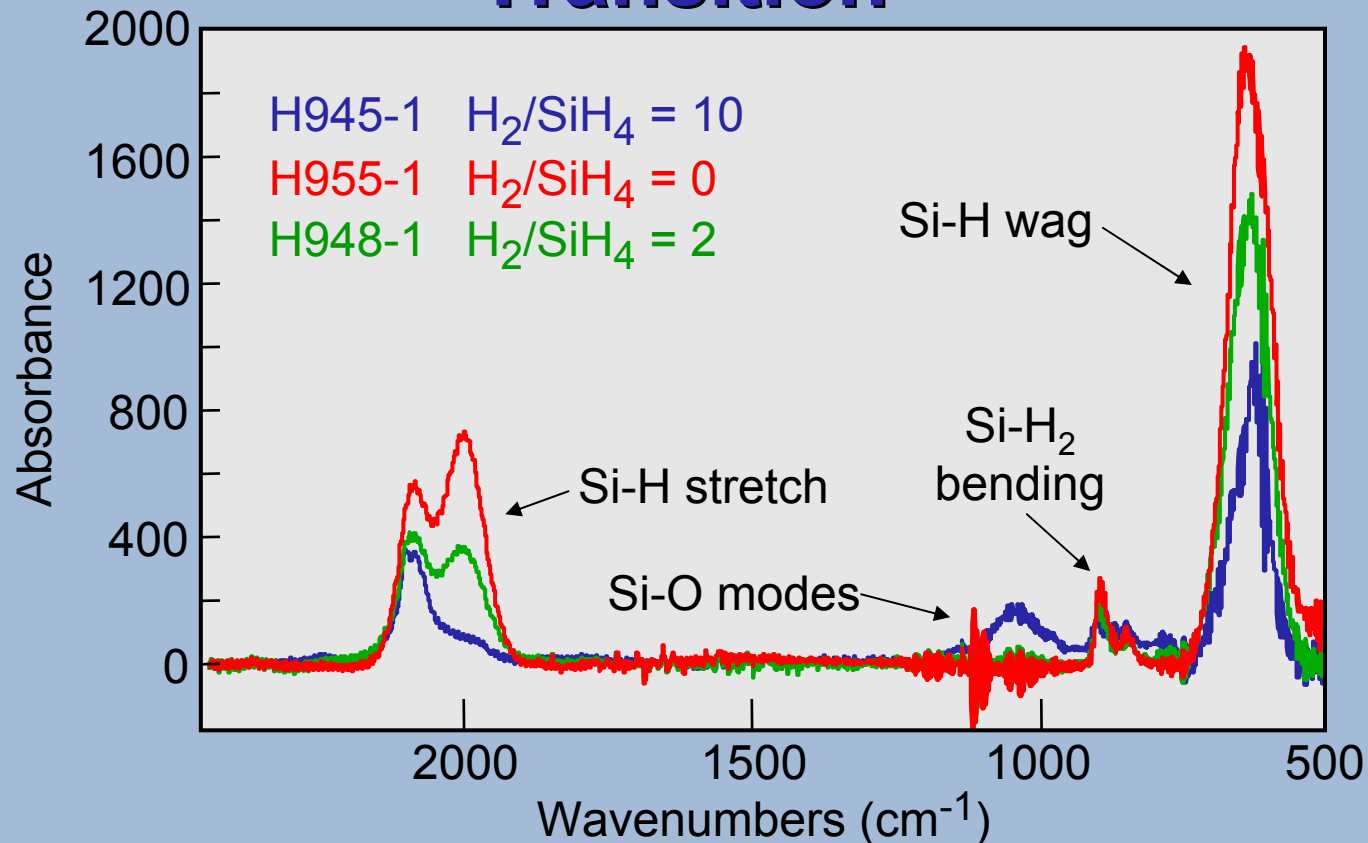- Low-gap photoluminescence measurements and mapping

03532074

Impurity Concentrations in Crystalline Silicon
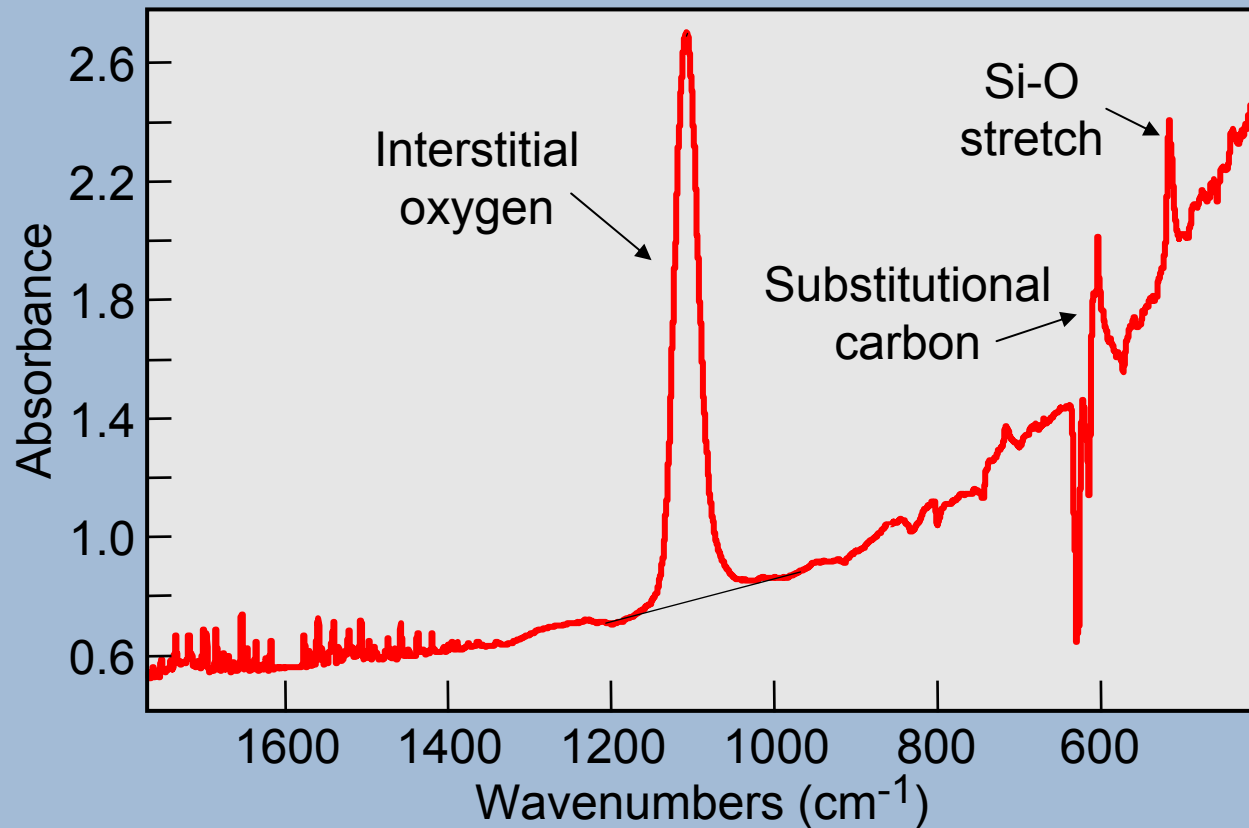
- Impurity content and process control
- Oxygen precipitates — related to material quality
- Study of SiN_x and SiC_x layers

03532075

Amorphous-Microcrystalline Silicon Transition

H945-1 $H_2/SiH_4 = 10$
H955-1 $H_2/SiH_4 = 0$
H948-1 $H_2/SiH_4 = 2$

Si-H wag

Si-H stretch

Si-H_2 bending

Si-O modes

Absorbance

Wavenumbers (cm^{-1})

- Si-H infrared bonding configurations are related to microcrystallinity
- Higher crystalline volume fractions favor increased oxidation — measure of device quality

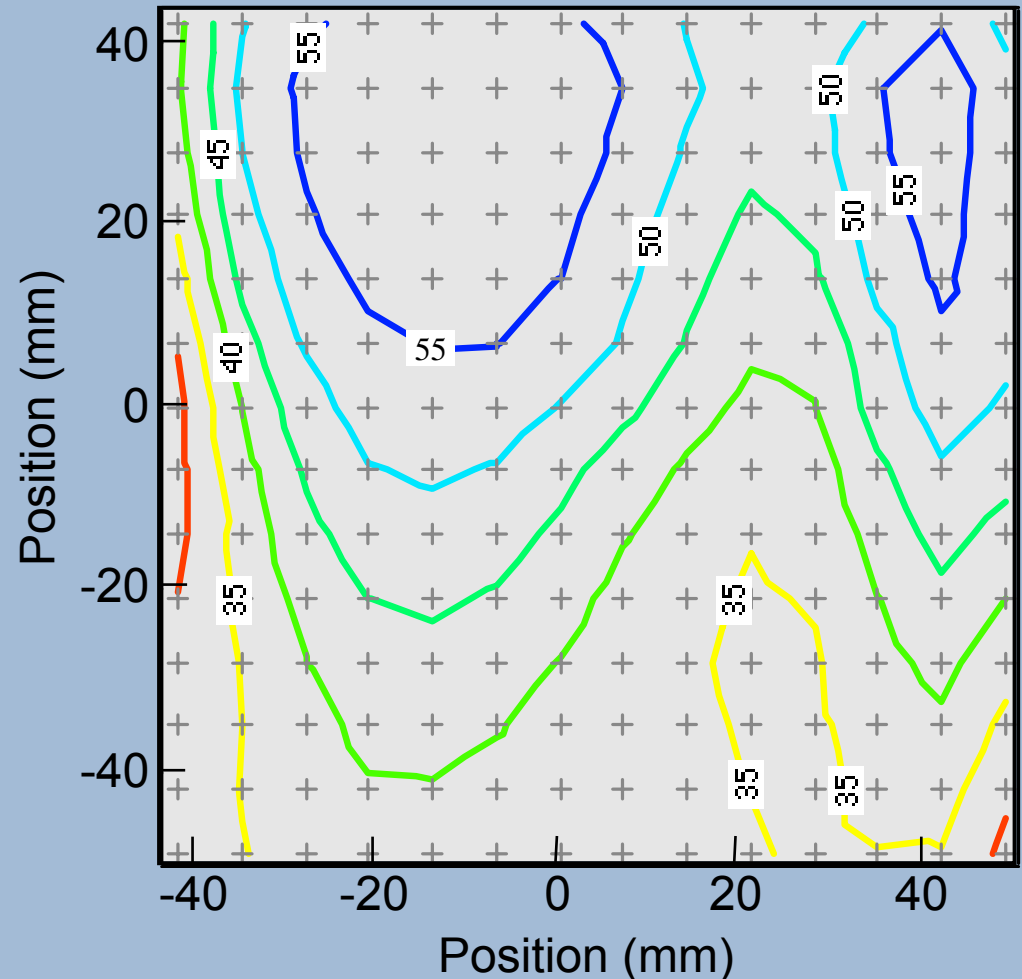03532076

a-SiGe:H Alloys
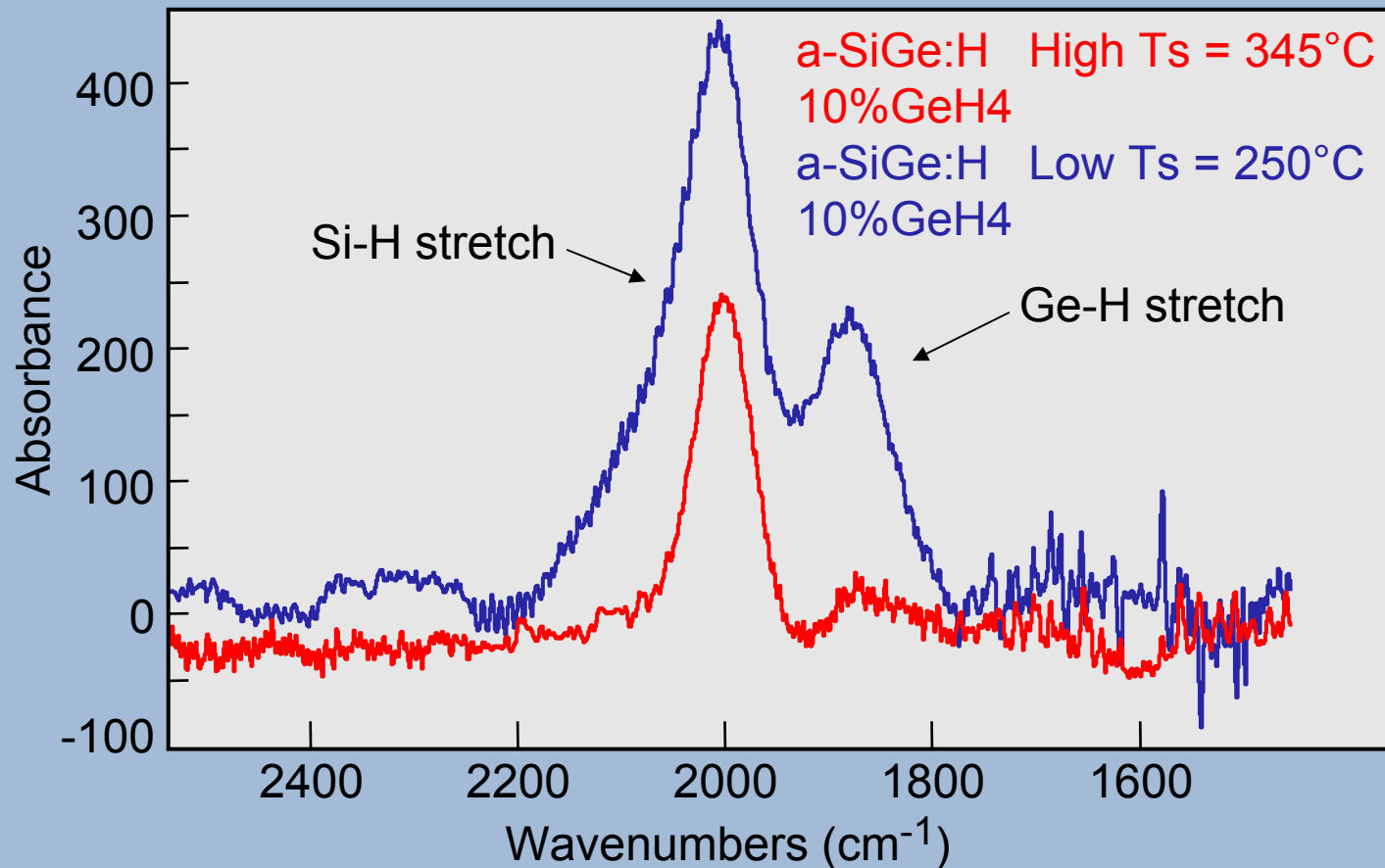
- Low-gap alloy in tandem devices
- Increased Ge-H bonding produces higher-quality alloys

03532077

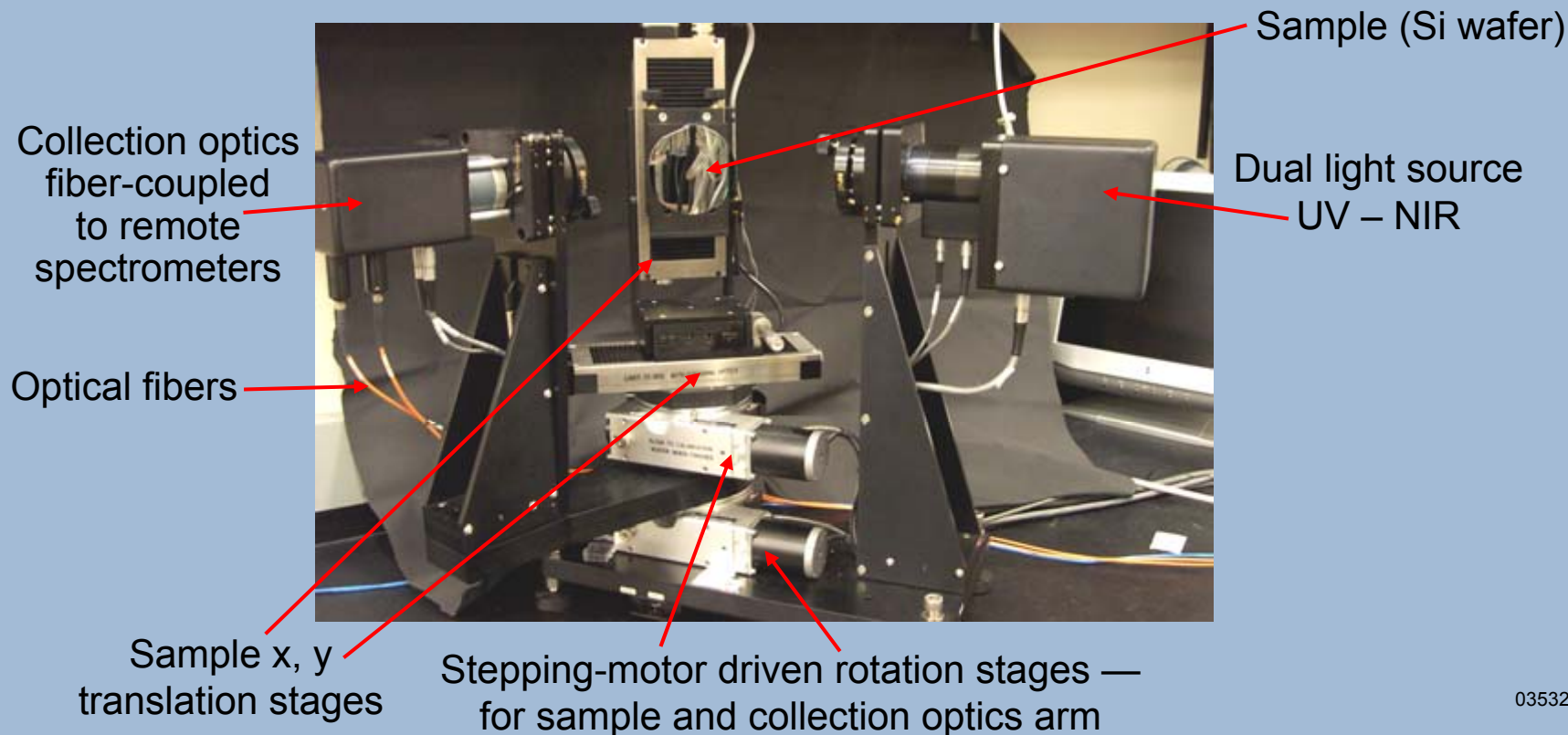# Transparent Conducting Oxide Films — Uniformity Map

- Support of combinatorial growth efforts
- Reflectance and transmittance maps
- Nondestructive measure of transport properties through determination of plasma frequency


03532078

Variable Angle Spectroscopic Ellipsometer

- Rotating compensator ellipsometer
- Automated variable angle measurement
- Sample translation and mapping
- Small-spot focusing ability (~1 mm spot size)
- Dual array detectors, 0.7–5.0 eV range, spectra in a few seconds

Sample (Si wafer)

Collection optics fiber-coupled to remote spectrometers

Dual light source UV – NIR

Optical fibers

Sample x, y translation stages

Stepping-motor driven rotation stages — for sample and collection optics arm

03532079

Optical Properties of Ordered $Ga_{0.51}In_{0.49}P$

- $Ga_{0.51}In_{0.49}P$ is a critical component of multi-junction, high efficiency solar cells
- Spontaneous ordering of Ga and In along (111) occurs during MOCVD growth
- Ordering reduces the bandgap and causes optical anisotropy
- These effects depend on the degree of ordering
  - which can be controlled during growth
- Accurate modeling of GaInP-based PV requires accurate optical constants

(111)

50.8°

hν

θ

(111) Ordering planes
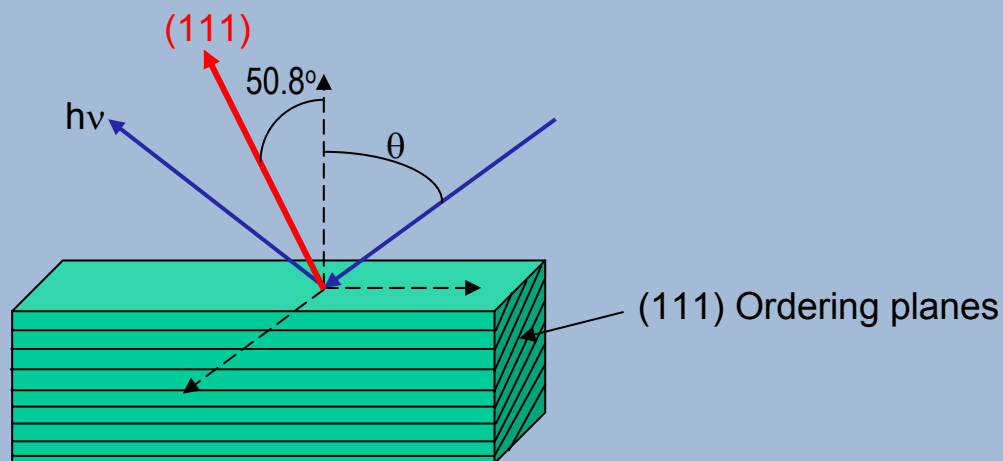
Crystal cleaves along (110), ($\bar{1}$10), (1$\bar{1}$0), and ($\bar{1}\bar{1}$0) planes

- Ellipsometry spectra are measured for various sample orientations to determine anisotropic optical constants

03532080

$Ga_{0.51}In_{0.49}P$ Optical Properties vs. Ordering

e-Axis Optical Constants

o-Axis Optical Constants
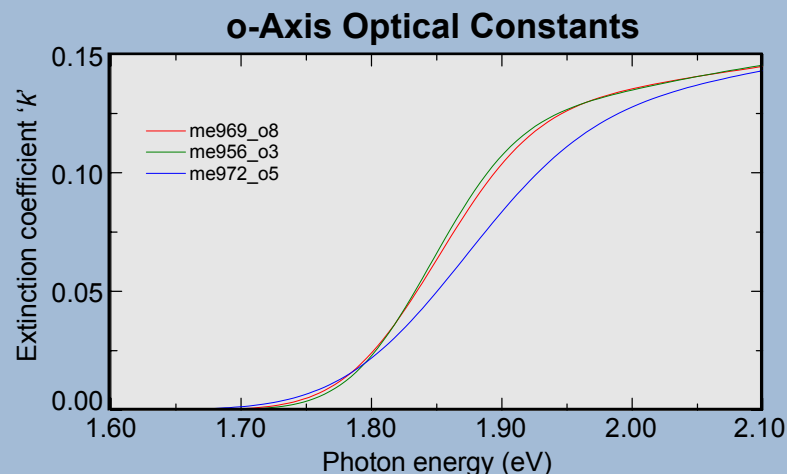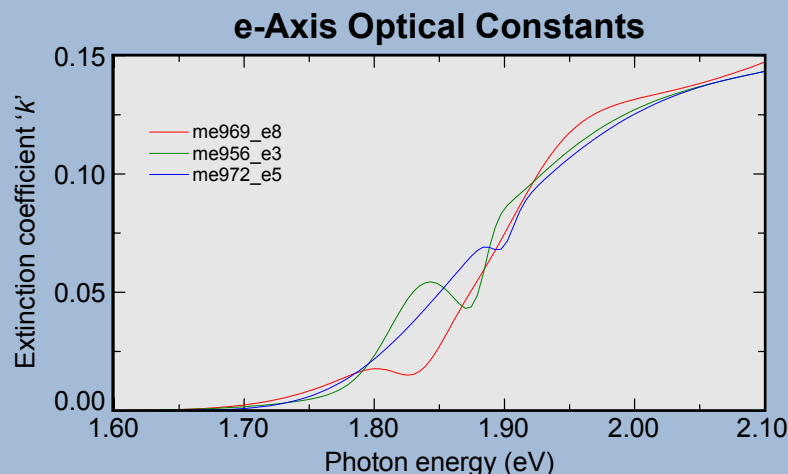
- Degree of ordering expressed in terms of ordering parameter h, 0 < h < 1

- In figures above, red corresponds to h = 0.45, green h = 0.31, and blue h = 0.10

- Extraordinary optical constants, on left side, show splitting of valence band max due to reduced symmetry produced by ordering

- Ordinary optical constants on right side shows reduced band gap with ordering

03532081

In-situ Real Time Spectroscopic Ellipsometry Studies of a-Si:H Growth

- NREL silicon materials team currently working to optimize HIT (heterojunction with intrinsic layer) solar cells
- Devices require very thin amorphous silicon layers on silicon substrate
- Efficiencies as high as 21% have been achieved — because of very effective surface passivation by a-Si:H layer on silicon wafer

100–300 Å p-type a-Si:H
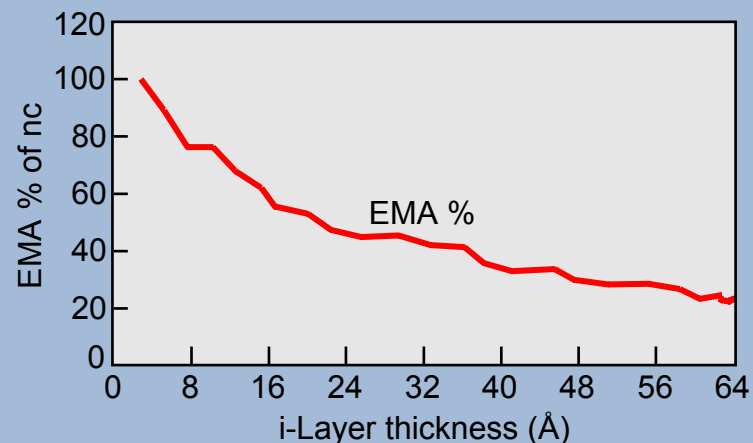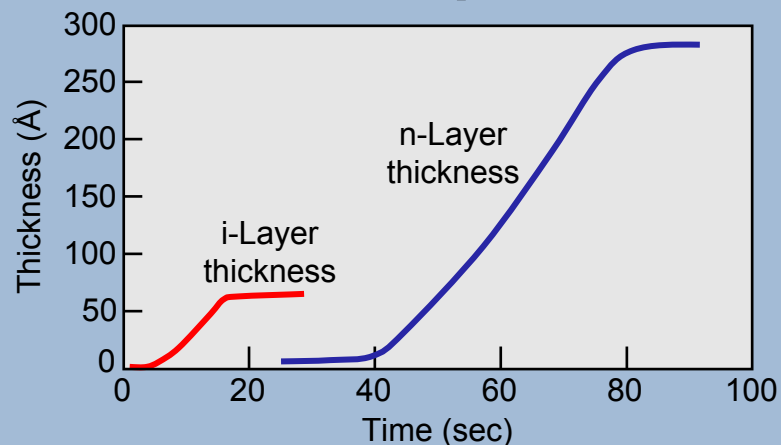
50 A undoped a-Si:H

n-Type silicon wafer
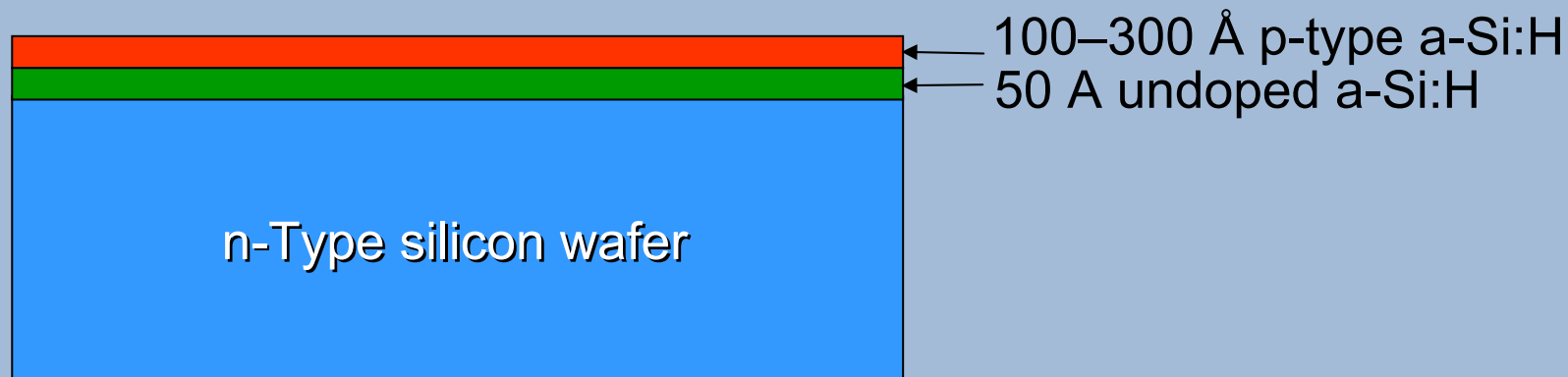
- Accurate thickness control requires real-time feedback — growth rates change with filament aging and changes in deposition gas flow rates, etc.
- Passivation requires immediate a-Si:H deposition at interface — epitaxial deposition on wafer surface hinders passivation effect of a-Si:H — c-Si interface

03532082

In-Situ RTSE Provides Real-time Feedback and Post-deposition Analysis of Crystallinity

03532083